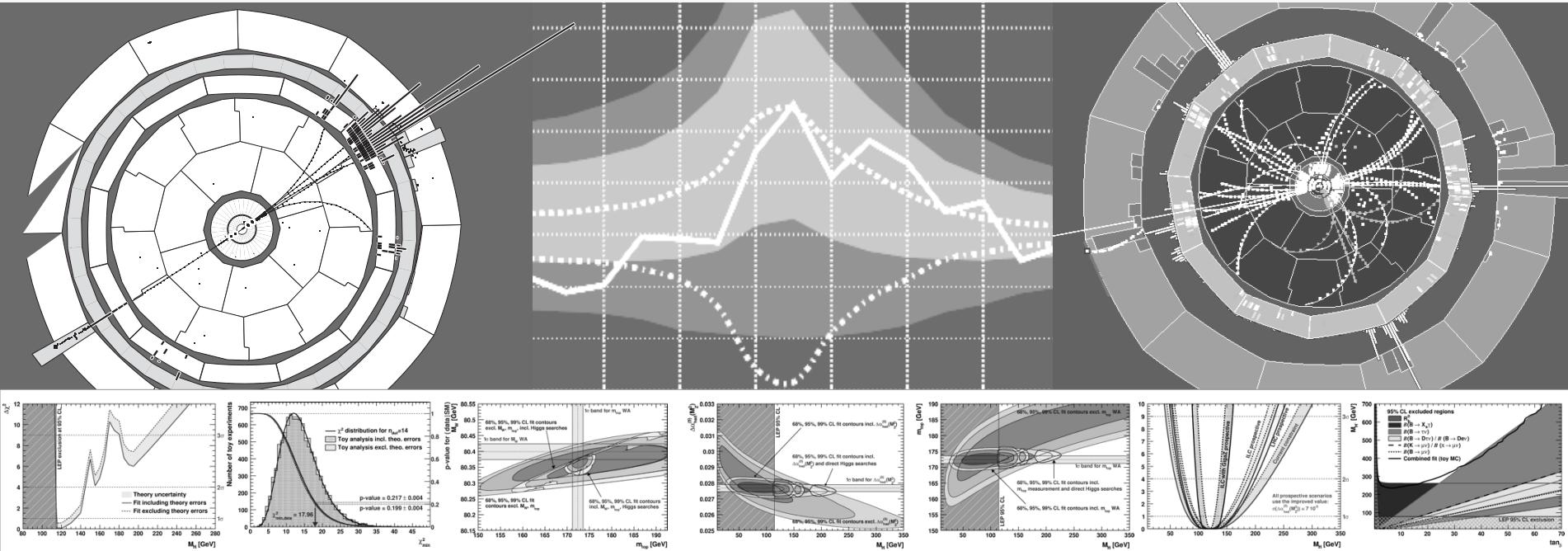


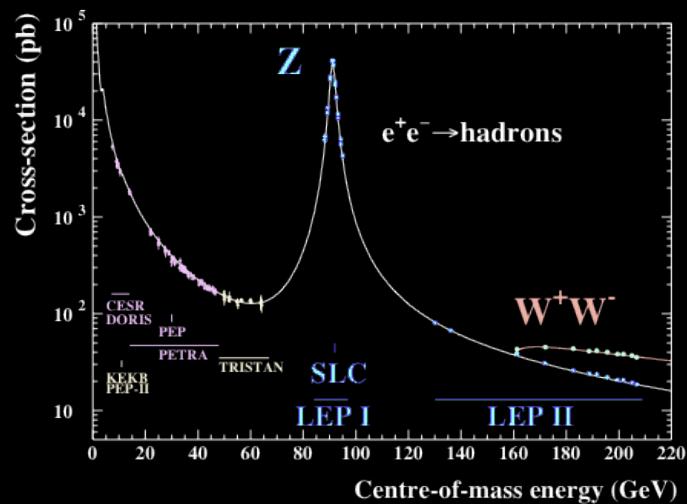
(Constraints from) Electroweak Precision Measurements – the LEP (& SLC) Legacy

Andreas Hoecker (CERN)

Challenges for Precision Physics at the LHC, Paris, December 15 – 18, 2010



Precision Measurements at LEP and SLC



Since the Z^0 boson couples to all fermion-antifermion pairs, it is an ideal laboratory for studying electroweak and strong interactions

Measurements at the Z Pole

Electroweak precision data measured at the Z^0 -resonance

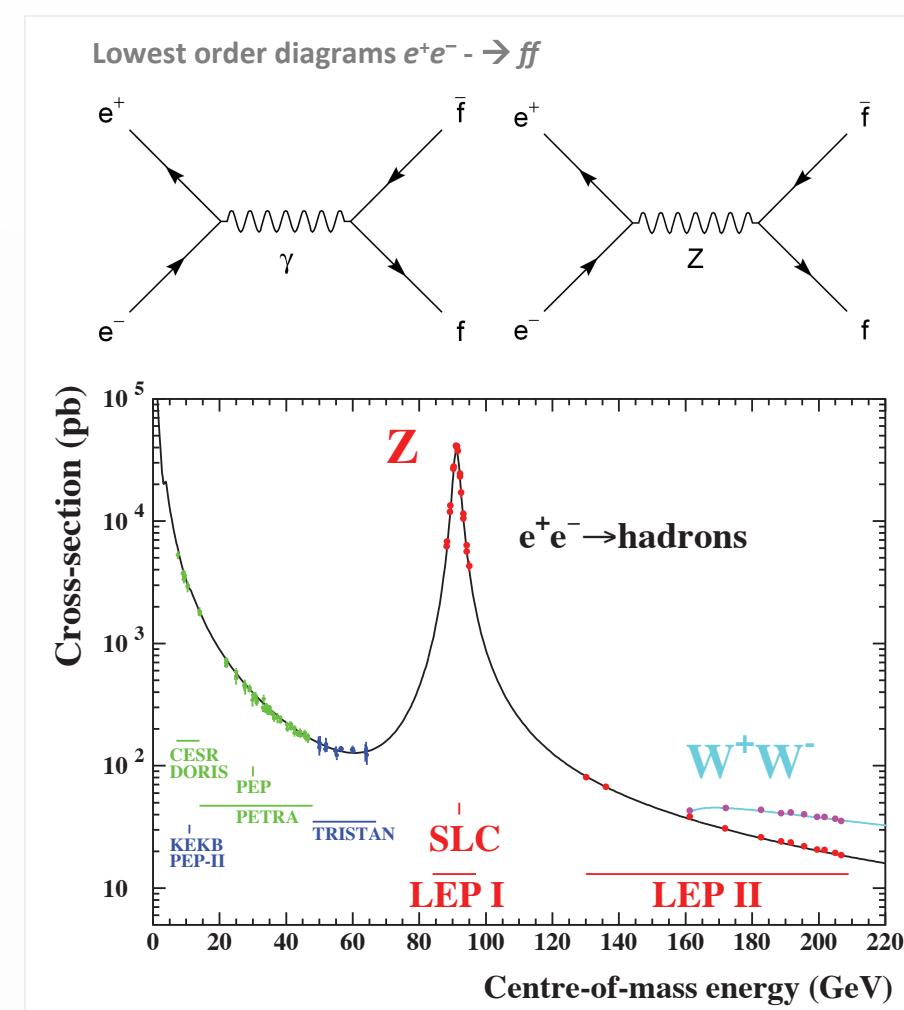
Process under study: $e^+e^- \rightarrow f\bar{f}$

- $f =$ all fermions (quarks, charged leptons, neutrinos) light enough to be pair produced

Hadronic cross-section:

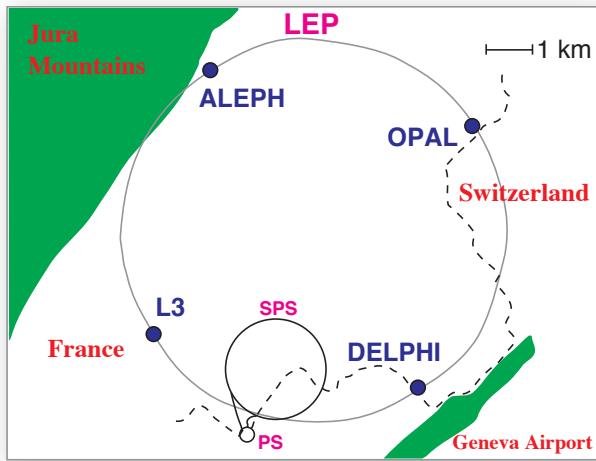
- s^{-1} fall-off due to virtual photon exchange
- Resonance at $\sqrt{s} = M_Z$
- For $\sqrt{s} > 2M_W$: pair-production of W 's kinematically allowed
- Measurements around M_Z : SLC, LEP I

Combined paper LEP + SLC:
Phys. Rept. 427, 257 (2006)

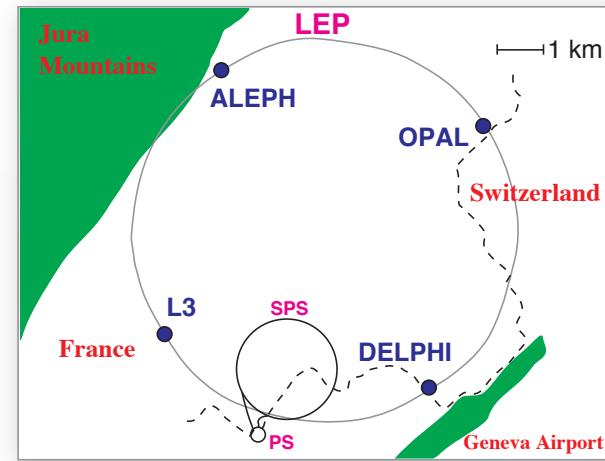


Measurements at the Z Pole (and beyond)

LEP I (1989 – 1995)



LEP II (1996 – 2000)

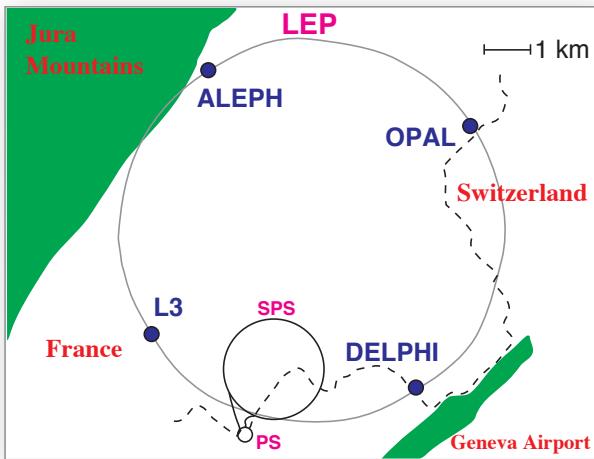


- Four experiments: ADLO
- $\sqrt{s} \sim M_Z$
- \sqrt{s} extremely well measured (2×10^{-5})
- Peak $L = 2 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
 - 1000 Z's per hour per experiment
 - “Z-Factory”
- In total: ~17 million Z decays (SLD: 600k)

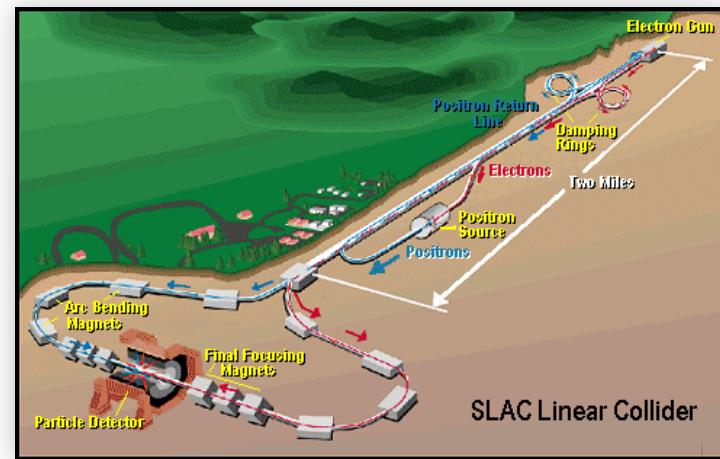
- Four experiments: ADLO
- $161 \text{ GeV} < \sqrt{s} \sim 207 \text{ GeV}$
 - 700 pb^{-1} per experiment
 - 12 000 W pairs per experiment
- Higgs sensitivity up to 115 GeV

Measurements at the Z Pole

LEP I (1989 – 1995)



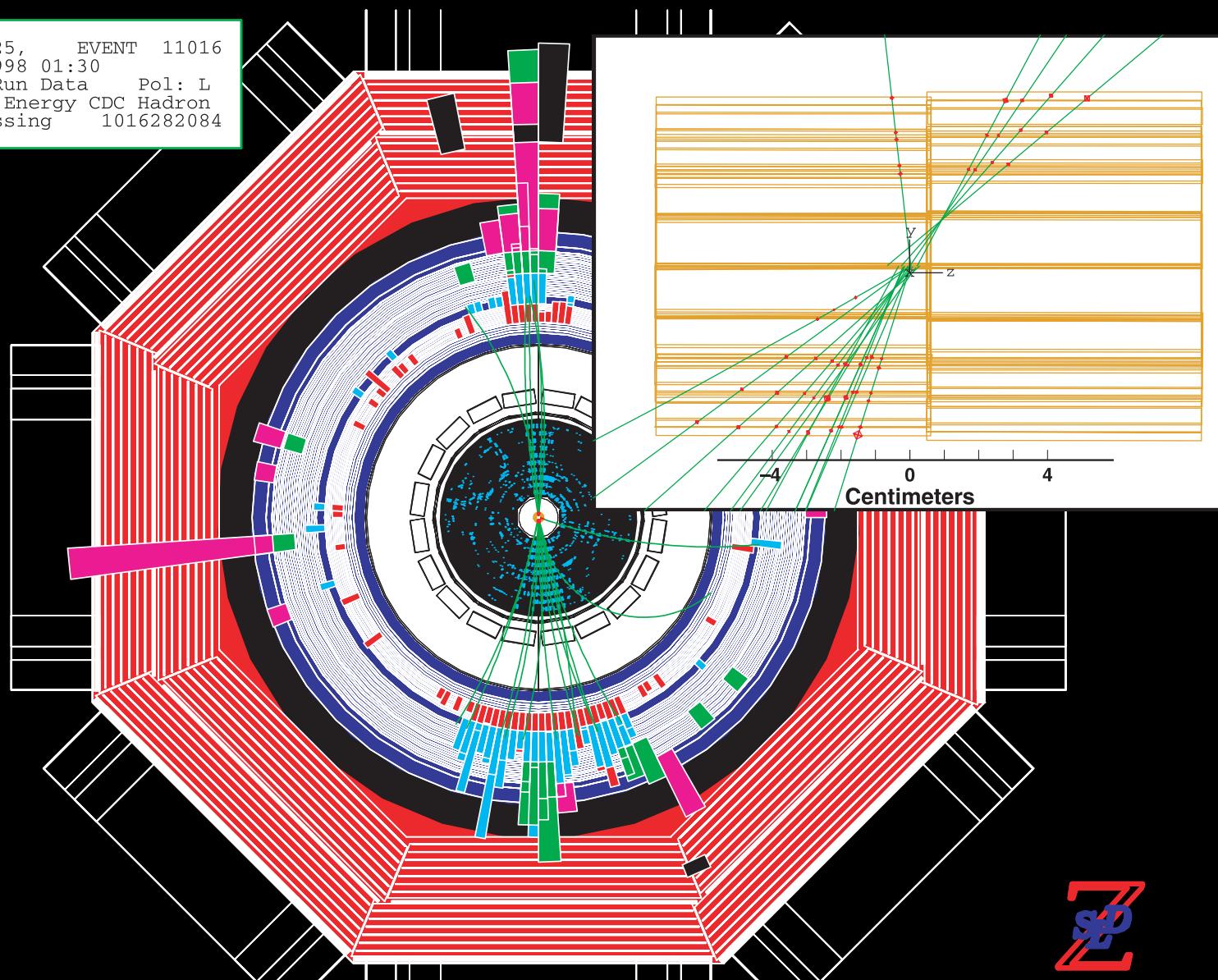
SLC (1989 – 1998)



- Four experiments: ADLO
- $\sqrt{s} \sim M_Z$
- \sqrt{s} extremely well measured (2×10^{-5})
- Peak $L = 2 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
 - 1000 Z's per hour per experiment
 - “Z-Factory”
- In total: ~17 million Z decays (SLD: 600k)

- Low repetition rate (120 Hz cf. LEP: 45 kHz)
- Longitudinally polarized electron beam (up to $P_e \sim 80\%$, known to 0.5%)
- Small beam dimensions ($1.5 \times 0.7 \mu\text{m}^2$, LEP: $150 \times 5 \mu\text{m}^2$) + low bunch rate allowed use of slow but high-res. CCD arrays
→ superior vertex reconstruction

Run 42725, EVENT 11016
9-APR-1998 01:30
Source: Run Data Pol: L
Trigger: Energy CDC Hadron
Beam Crossing 1016282084



A $Z \rightarrow bb$ event with displaced vertices seen in SLD

Electroweak Physics at the Z Pole

A look at the theory – tree level relations

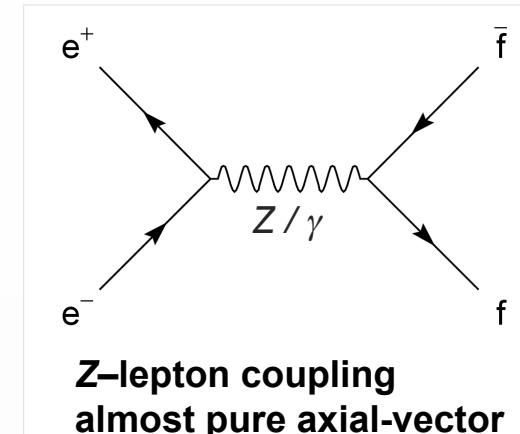
Vector and axial-vector couplings for $Z \rightarrow ff$ in SM:

$$g_{V,f}^{(0)} = g_{L,f}^{(0)} + g_{R,f}^{(0)} = I_3^f - 2Q_f \sin^2 \theta_W \quad \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$
$$g_{A,f}^{(0)} = g_{L,f}^{(0)} - g_{R,f}^{(0)} = I_3^f$$

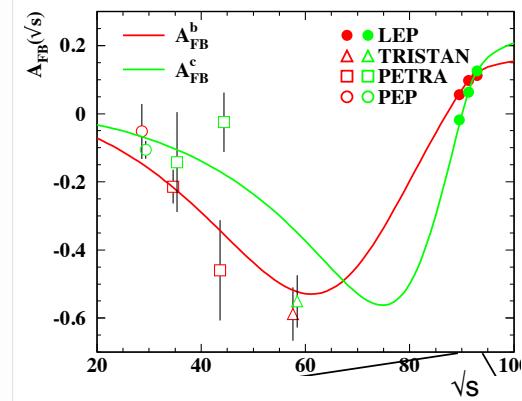
Electroweak unification: relation between weak and electromagnetic couplings:

$$G_F = \frac{\pi \alpha(0)}{\sqrt{2} M_W^2 \left(1 - M_W^2/M_Z^2\right)}, \quad M_W^2 = \frac{M_Z^2}{2} \cdot \left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Gauge sector of SM on tree level is given by 3 free parameters, e.g.: α , M_Z , G_F (best known!)



(γ pure vector \rightarrow large off-peak interference \rightarrow could establish Z-fermion coupling at PETRA, interesting for Z' searches via interference)



Electroweak Physics at the Z Pole

Radiative corrections –
modifying propagators and vertices

Significance of radiative corrections
can be illustrated by verifying tree level
relation:

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

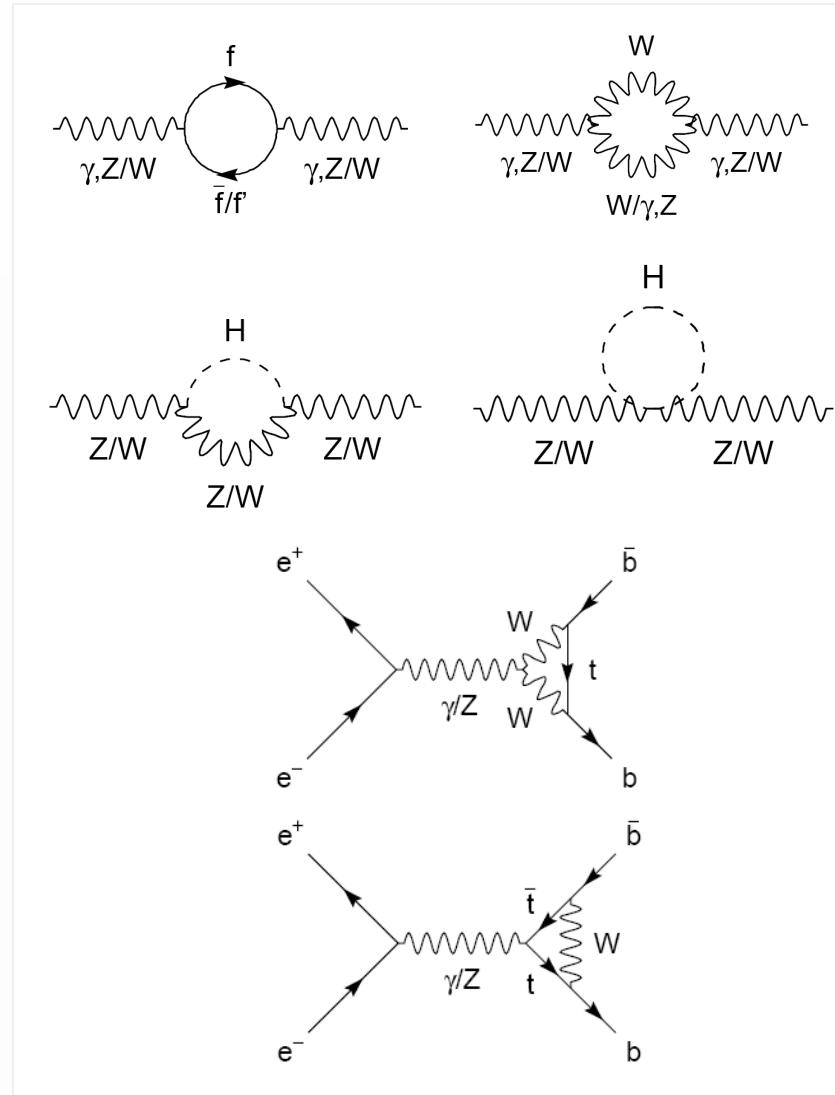
- Using the measurements:

$$M_W = (80.399 \pm 0.023) \text{ GeV}$$

$$M_Z = (91.1875 \pm 0.0021) \text{ GeV}$$

one predicts: $\sin^2 \theta_W = 0.22284 \pm 0.00045$

which is 18σ away from the experimental
value obtained by combining all asymmetry
measurements: $\sin^2 \theta_W = 0.23153 \pm 0.00016$



Electroweak Physics at the Z Pole

Radiative corrections –
modifying propagators and vertices

Parametrisation of radiative corrections:

“electroweak form-factors”: ρ , κ , Δr

- Modified (“effective”) couplings at the Z pole:

$$g_{V,f} = \sqrt{\rho_Z^f} \left(I_3^f - 2Q^f \sin^2 \theta_{\text{eff}}^f \right)$$

$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

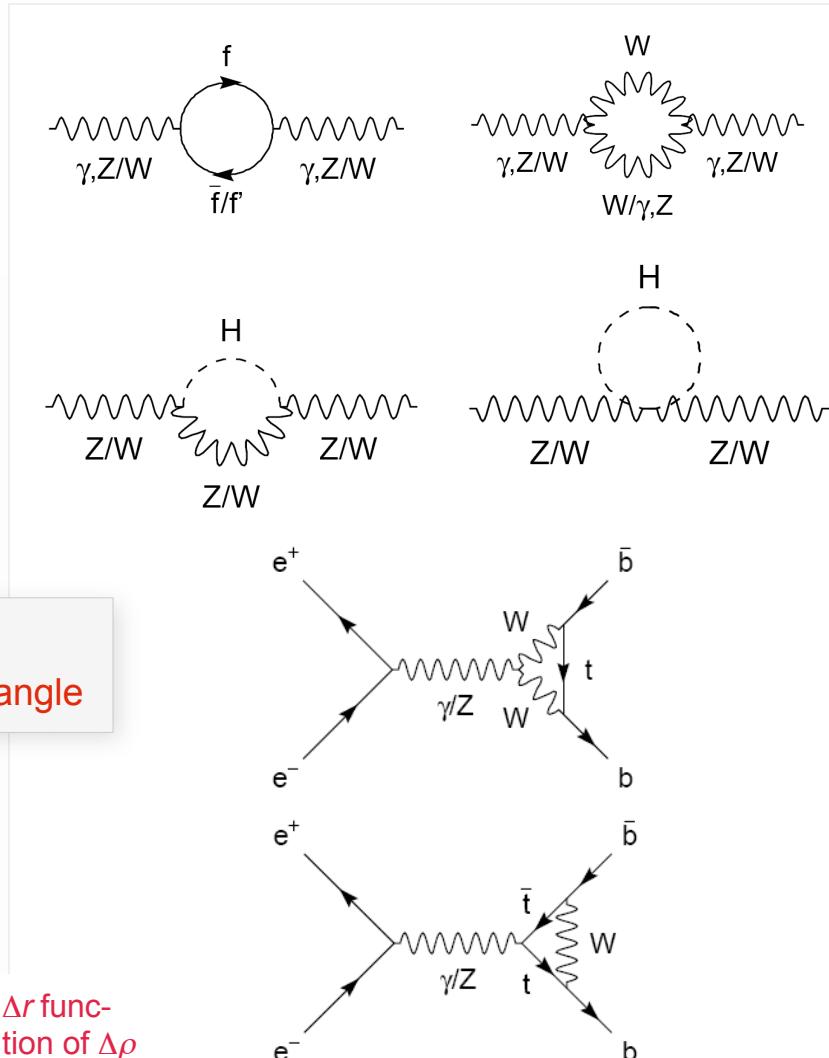
$$\sin^2 \theta_{\text{eff}}^f = \kappa_Z^f \sin^2 \theta_W$$

ρ : overall scale

κ : on-shell mixing angle

- Modified W mass:

$$M_W^2 = \frac{M_Z^2}{2} \cdot \left(1 + \sqrt{1 - \frac{\sqrt{8\pi\alpha}}{G_F M_Z^2 \cdot (1 - \Delta r)}} \right) \quad \leftarrow \Delta r \text{ function of } \Delta \rho$$



Electroweak Physics at the Z Pole

Radiative corrections – modifying propagators and vertices

Leading order terms ($M_W \ll M_H$)

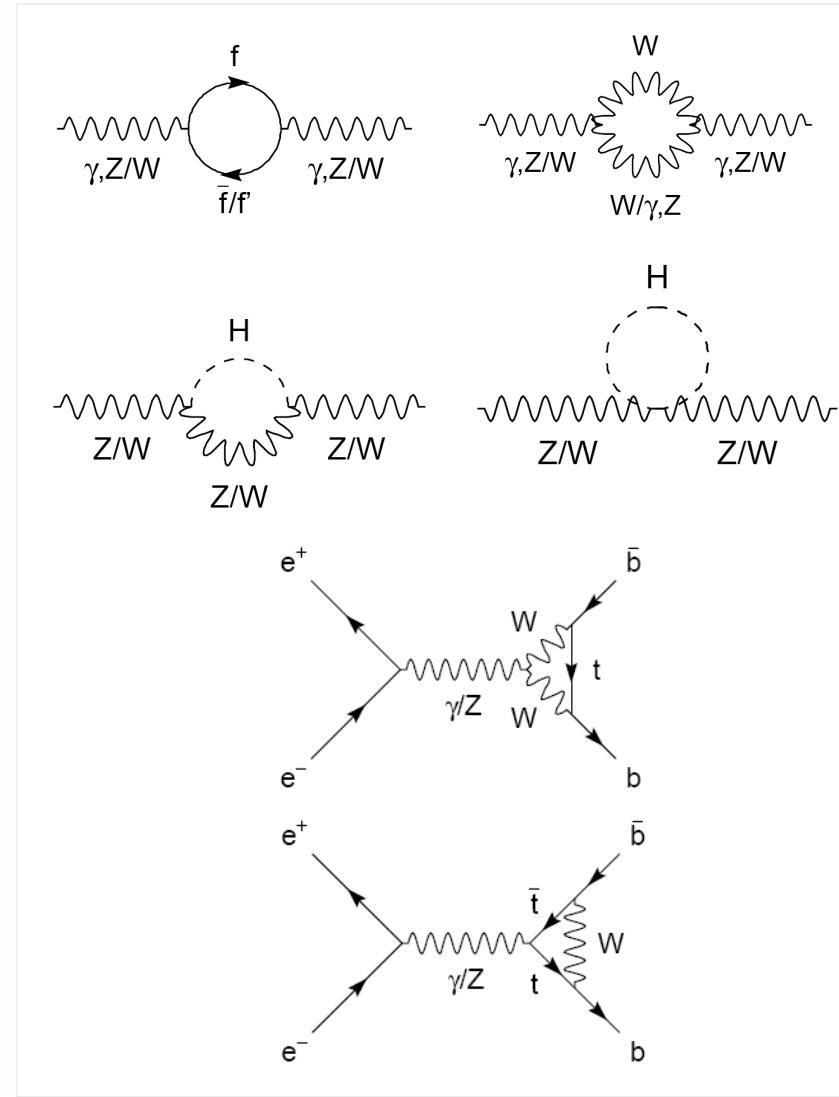
- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

$$\Delta\rho_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2} \left[\frac{m_t^2}{M_W^2} - \tan^2 \theta_W \left(\ln \frac{M_H^2}{M_W^2} - \frac{5}{6} \right) + \dots \right]$$

$$\Delta\kappa_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2} \left[\frac{m_t^2}{M_W^2} \cot^2 \theta_W - \frac{10}{9} \left(\ln \frac{M_H^2}{M_W^2} - \frac{5}{6} \right) + \dots \right]$$

- and flavour-specific vertex corrections, which are very small, except for top quarks, owing to large mass and $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \dots$$



Electroweak Physics at the Z Pole

Radiative corrections – modifying propagators and vertices

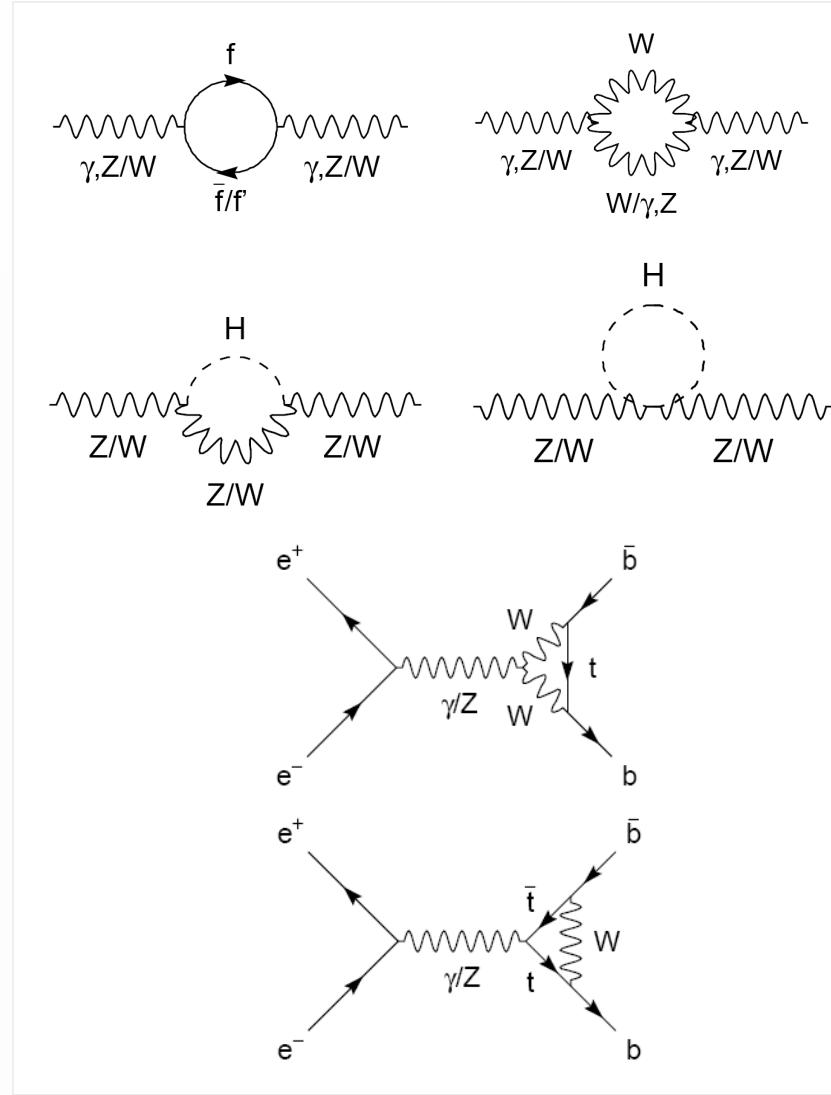
Leading order terms ($M_H \ll M_W$)

- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

**Radiative corrections
allow us to test the SM
and to constrain unknown
SM parameters**

- and flavour-specific vertex corrections, which are very small, except for top quarks, due to large $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \dots$$



Measurements at the Z Pole

Example – electroweak cross-section formula for unpolarised beams (LEP)

$$\frac{2s}{\pi} \frac{1}{N_c^f} \frac{d\sigma_{ew}(e^+e^- \rightarrow f\bar{f})}{d\cos\theta} = |\alpha(s) \cdot Q_f|^2 (1 + \cos^2\theta) - 8\text{Re}\left\{\alpha^*(s)Q_f\chi_{BW}(s)\left[g_{V,e}g_{V,f}(1 + \cos^2\theta) + 2g_{A,e}g_{A,f}\cos\theta\right]\right\} + 16|\chi_{BW}(s)|^2\left[\left(g_{V,e}^2 + g_{A,e}^2\right)\left(g_{V,f}^2 + g_{A,f}^2\right)(1 + \cos^2\theta) + 8\text{Re}\left\{g_{V,e}g_{A,e}^*\right\}\text{Re}\left\{g_{V,f}g_{A,f}^*\right\}\cos\theta\right]$$

- Pure γ exchange
- γ -Z interference
- Pure Z exchange

Neglects photon ISR & FSR, gluon FSR, fermion masses

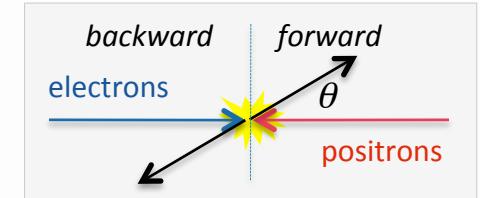
The $\propto (1 + \cos^2\theta)$ terms contribute to total cross-sections

- Measure cross-sections around M_Z via corrected event counts:

$$\sigma = (N_{\text{sel}} - N_{\text{bg}})/\varepsilon_{\text{sel}} L$$

The $\propto \cos\theta$ terms contribute only to asymmetries

- Measure *Forward–Backward asymmetries* in angular distributions final-state fermions: $A_{FB} = (N_F - N_B)/(N_F + N_B)$



Other asymmetries (not in above cross section formula)

- Dependence of Z^0 production on helicities of initial state fermions (SLC) \rightarrow *Left–Right asymmetries*
- Polarisation of final state fermions (can be measured in tau decays)

Measurements at the Z Pole

Total hadronic cross section – measurement and prediction

Total cross-section (from $\cos\theta$ symmetric terms) expressed in Breit-Wigner form:

$$\sigma_{ff}^Z = \sigma_{ff}^0 \cdot \frac{s \cdot \Gamma_Z^2}{(s - M_Z^2)^2 + s^2 \Gamma_Z^2 / M_Z^2} \cdot R_{\text{QED}}$$
$$\sigma_{ff}^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_{ee} \Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

Corrected for
QED radiation

Partial widths add up to full width: $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadronic}} + \Gamma_{\text{invisible}}$

- Measured cross sections depend on products of partial and total widths
- Highly correlated set of parameters !

Instead: use less correlated set of measurements

- Z mass and width: M_Z (2×10⁻⁵ accuracy !), Γ_Z
 - Hadronic pole cross section: σ_{had}^0
 - Three leptonic ratios (use lepton-univ.): $R_\ell^0 = R_e^0 = \Gamma_{\text{had}}/\Gamma_{ee}$, R_μ^0 , R_τ^0
 - Hadronic width ratios: $R_b^0 = \Gamma_{b\bar{b}}/\Gamma_{\text{had}}$, R_c^0
- Taken from LEP:
• precise √s
• high statistics
- Include also SLD:
• higher effi./purity for heavy quarks

Measurements at the Z Pole

Initial and final state QED radiation

Measured cross-section (and asymmetries) are modified by initial and final state QED radiation

- Effects are corrected for by the collaborations (using the programs TOPAZ0 and ZFITTER)

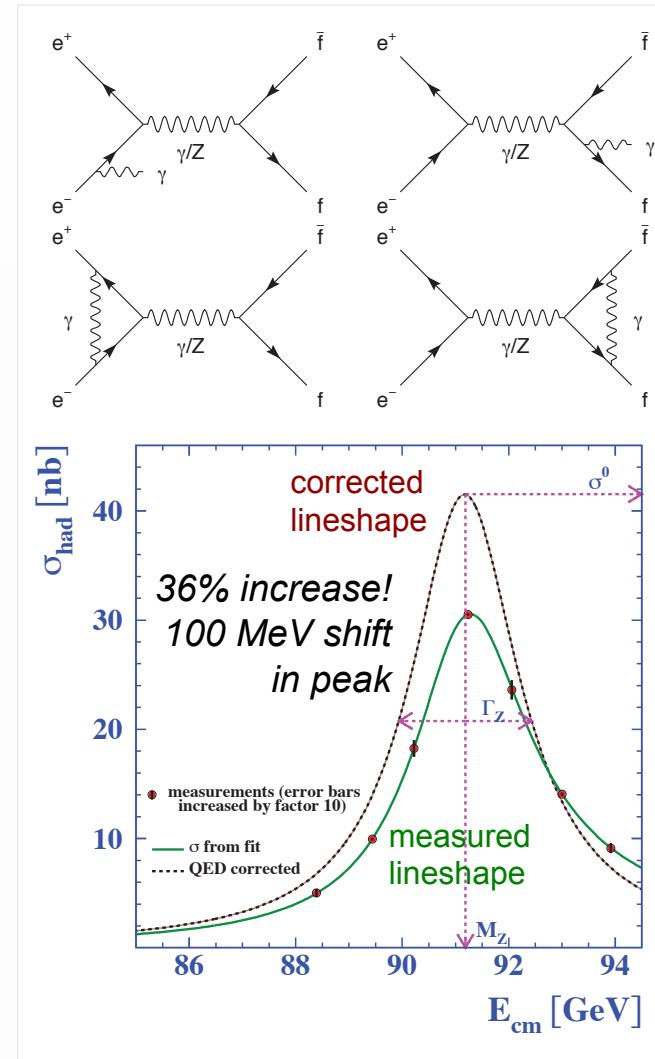
$$\sigma(s) = \int_{4m_f^2/s}^1 dz \cdot H_{\text{QED}}^{\text{tot}}(z, s) \cdot \sigma(zs)$$

Convolution of kernel cross section by QED radiator function

- Very large corrections applied in some cases!*
- Measured observables become “pseudo-observables”
- E.g.*, hadronic pole-cross section σ_{had}^0

In the electroweak fit the published “pseudo-observables” are used

Important: these QED corrections are independent of the electroweak corrections discussed before!



Measurements at the Z Pole

Partial width – sensitive to QCD and QED corrections

Partial width are defined **inclusively**, i.e., they contain final state QED and QCD vector and axial-vector corrections via “radiator functions”: $R_{A,f}$, $R_{V,f}$

$$\Gamma_{\bar{f}f} = N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi} \left(|g_{A,f}|^2 R_{A,f} + |g_{V,f}|^2 R_{V,f} \right)$$

QCD corrections only affect final states with quarks

- To first order in α_s corrections are flavour independent and identical for A and V

$$R_{V,QCD} = R_{A,QCD} = R_{QCD} = 1 + \frac{\alpha_s(M_Z^2)}{\pi} + \dots = 1 + 0.038 + \dots$$

- 3NLO (!) calculation available [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]

QED corrections similar: $R_{V,QED} = R_{A,QED} = R_{QED} = 1 + \underbrace{\frac{3}{4} Q_f^2 \frac{\alpha(M_Z^2)}{\pi}}_{0.0019 \times Q_f^2} + \dots$ What is this?
(though much smaller due to $\alpha \ll \alpha_s$)

Digression: Running of $\alpha_{\text{QED}}(M_z)$

Define: photon vacuum polarisation function $\Pi_\gamma(q^2)$

$$i \int d^4x e^{iqx} \langle 0 | T J_{\text{em}}^\mu(x) (J_{\text{em}}^\nu(0))^\dagger | 0 \rangle = - (g^{\mu\nu} q^2 - q^\mu q^\nu) \Pi_\gamma(q^2)$$

Only vacuum polarisation “screens” electron charge

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)} \quad \text{with:} \quad \begin{aligned} \Delta\alpha(s) &= -4\pi\alpha \operatorname{Re} [\Pi_\gamma(s) - \Pi_\gamma(0)] \\ &= \Delta\alpha_{\text{lep}}(s) + \Delta\alpha_{\text{had}}(s) \end{aligned}$$

Leptonic $\Delta\alpha_{\text{lep}}(s)$ calculable in QED (known to 3-loops). However, quark loops are modified by long-distance hadronic physics, **cannot be calculated with perturbative QCD**

Way out: **Optical Theorem (unitarity)** ...

... and the subtracted dispersion relation of $\Pi_\gamma(q^2)$ (**analyticity**)

$$\text{Born: } \sigma^{(0)}(s) = \sigma(s)(\alpha/\alpha(s))^2$$

$$12\pi \operatorname{Im} \Pi_\gamma(s) = \frac{\sigma^{(0)}[e^+e^- \rightarrow \text{hadrons}]}{\sigma^{(0)}[e^+e^- \rightarrow \mu^+\mu^-]} \equiv R(s)$$



$$\Pi_\gamma(s) - \Pi_\gamma(0) = \frac{s}{\pi} \int_0^\infty ds' \frac{\operatorname{Im} \Pi_\gamma(s')}{s'(s' - s) - i\varepsilon} \quad \Rightarrow \quad \Delta\alpha_{\text{had}}(s) = -\frac{\alpha s}{3\pi} \operatorname{Re} \int_0^\infty ds' \frac{R(s')}{s'(s' - s) - i\varepsilon}$$

Digression: Running of $\alpha_{\text{QED}}(M_Z)$

Hadronic dispersion integral solved by combination of experimental data and perturbative QCD

$$\Delta\alpha_{\text{had}}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi} P \int_0^\infty ds' \frac{R(s')}{s'(s' - M_Z^2)}$$

The task is to properly correct, average and integrate the cross section data.

Use perturbative QCD where possible (“global quark–hadron duality” allows one to extend perturbative QCD into the non-continuum regions)

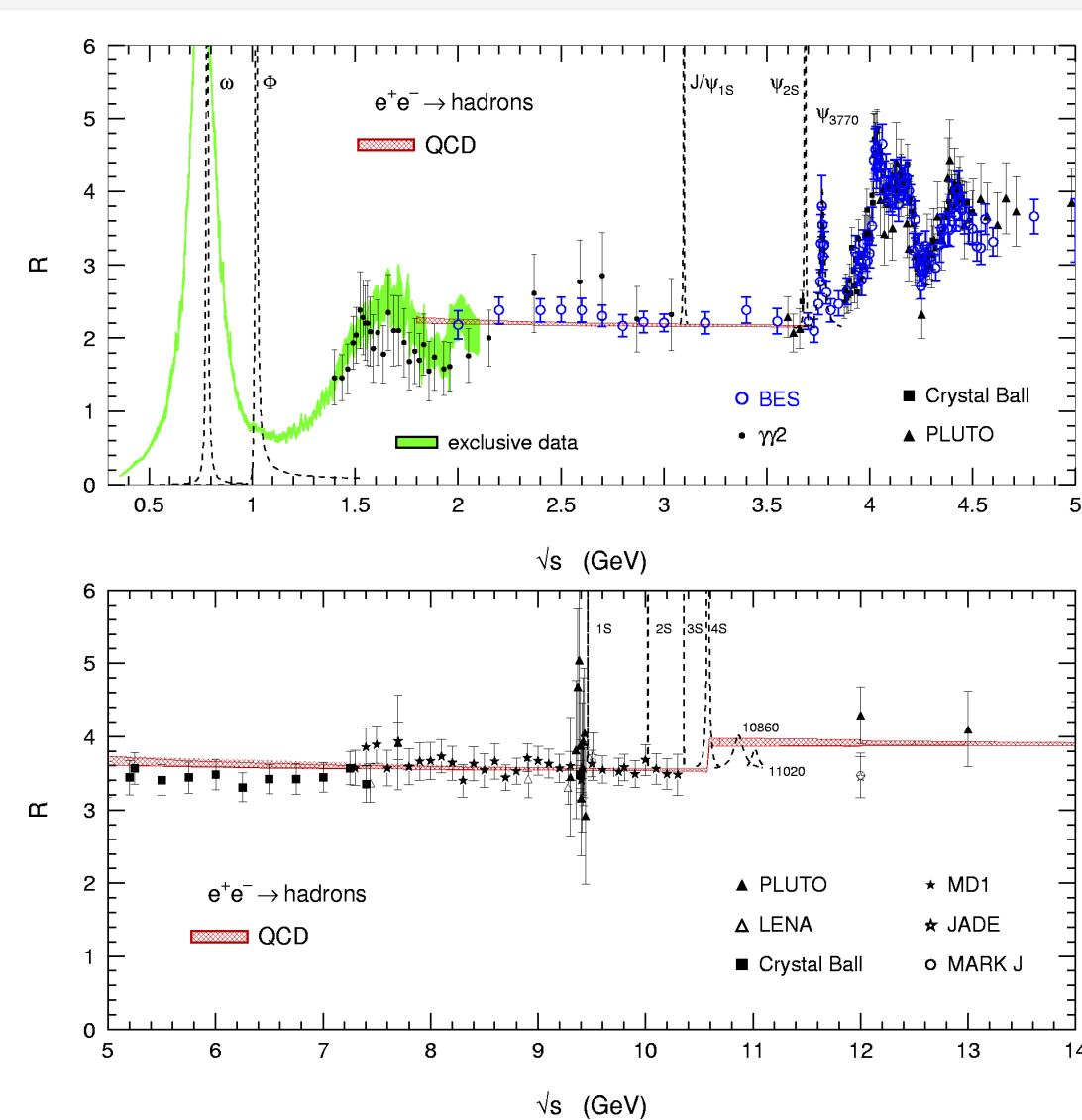
Traditionally separate:

$$\Delta\alpha_{\text{had}}(M_Z^2) = \Delta\alpha_{\text{had}}^{(5)}(M_Z^2) + \Delta\alpha_{\text{top}}(M_Z^2)$$

Results [DHMZ, arXiv:1010.4180 (2010)]

$$\begin{aligned} \Delta\alpha(M_Z^2) &= 0.03149769_{\text{lep}} \\ &+ 0.02749(10)_{\text{had (5)}} \\ &- 0.000072(02)_{\text{top}} \end{aligned}$$

$$\alpha^{-1}(M_Z^2) = 128.962 \pm 0.014$$



Digression: anomalous magnetic moment of the muon “ $g - 2$ ”

Contributing diagrams:

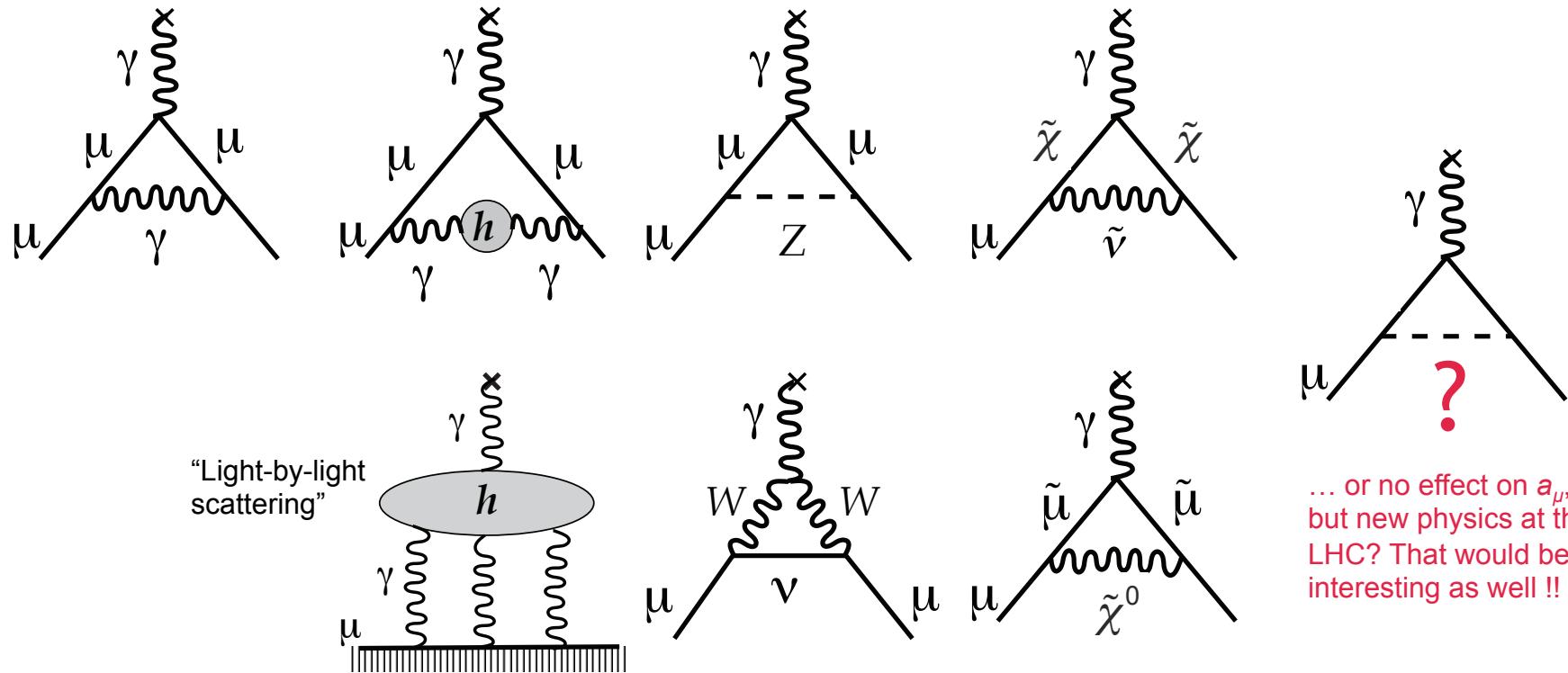
QED

Hadronic

Weak

SUSY... ?

... or some unknown
type of new physics ?



Dominant uncertainty in SM prediction from lowest-order hadronic term

Computed similarly as $\Delta\alpha_{\text{had}}$ via dispersion relation, but emphasis on low- \sqrt{s} cross section

Digression: anomalous magnetic moment of the muon

Experimental result (E821-BNL, 2004): $a_\mu = (11\ 659\ 208.9 \pm 5.4 \pm 3.3) \times 10^{-10}$

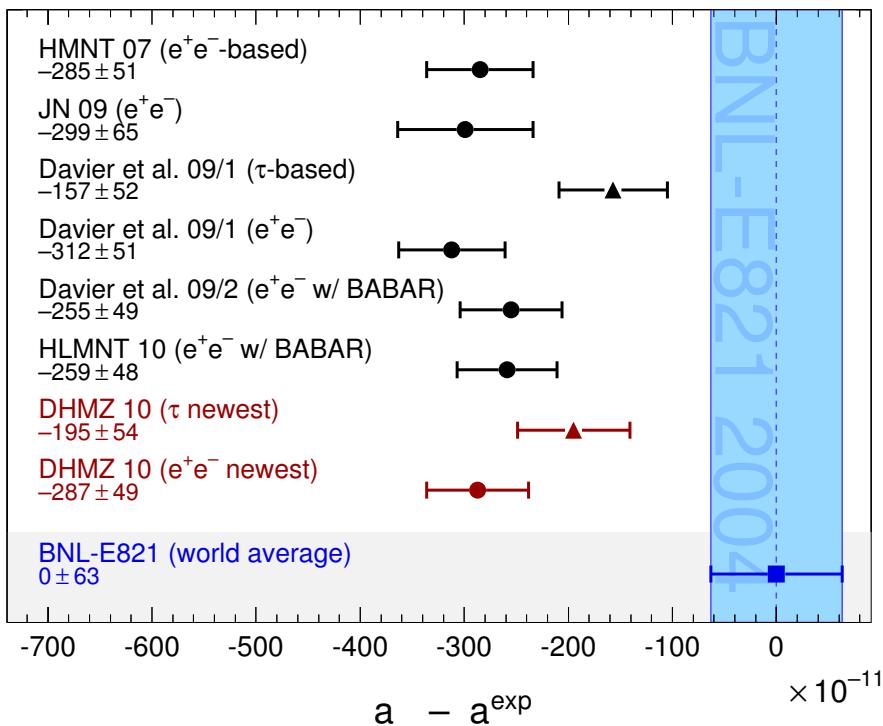
E821: PR D73,
072003 (2006)

Standard Model Prediction:

$$a_\mu^{\text{SM}}[\text{e}^+\text{e}^- \text{-based}] = (11\ 659\ 180.2 \pm 4.2_{\text{had,LO}} \pm 2.6_{\text{NLO}} \pm 0.2_{\text{QED+weak}}) \times 10^{-10}$$

$$a_\mu^{\text{SM}}[\tau \text{-based}] = (11\ 659\ 189.4 \pm 4.7_{\text{had,LO}} \pm 2.6_{\text{NLO}} \pm 0.2_{\text{QED+weak}}) \times 10^{-10}$$

DMHZ, arXiv:1010.4180



Observed Difference with Experiment:

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.7 \pm 8.0) \times 10^{-10} [\text{ee}]$$

$$= (19.5 \pm 8.3) \times 10^{-10} [\tau]$$

→ 3.6 / 2.4 "standard deviations"

Davier-Hoecker-Malaescu-Zhang, arXiv:1010.4180, 2010

The deviation is in the ball park of SUSY expectations with $O(0.1\text{--}1\text{ TeV})$ squarks and gluinos

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Partial width are defined **inclusively**, i.e., they contain final state QED and QCD vector and axial-vector corrections via “radiator functions”: $R_{A,f}$, $R_{V,f}$

$$\Gamma_{\bar{f}f} = N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi} \left(|g_{A,f}|^2 R_{A,f} + |g_{V,f}|^2 R_{V,f} \right)$$

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(though much smaller due to $\alpha \ll \alpha_s$)

Neutral Current Couplings

Asymmetry and polarisation – quantify parity violation

Distinguish vector and axial-vector couplings of the Z (i.e., $\sin^2\theta_{\text{eff}}^f$)

Convenient to use “asymmetry parameters”:

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = 2 \frac{g_{V,f}/g_{A,f}}{1 + (g_{V,f}/g_{A,f})^2} \quad \text{dependent on } \sin^2\theta_{\text{eff}}^f : \frac{\text{Re}(g_{V,f})}{\text{Re}(g_{A,f})} = 1 - 4|Q_f|\sin^2\theta_{\text{eff}}^f$$

Via *final state (FS) angular distribution* in unpolarised scattering (LEP)

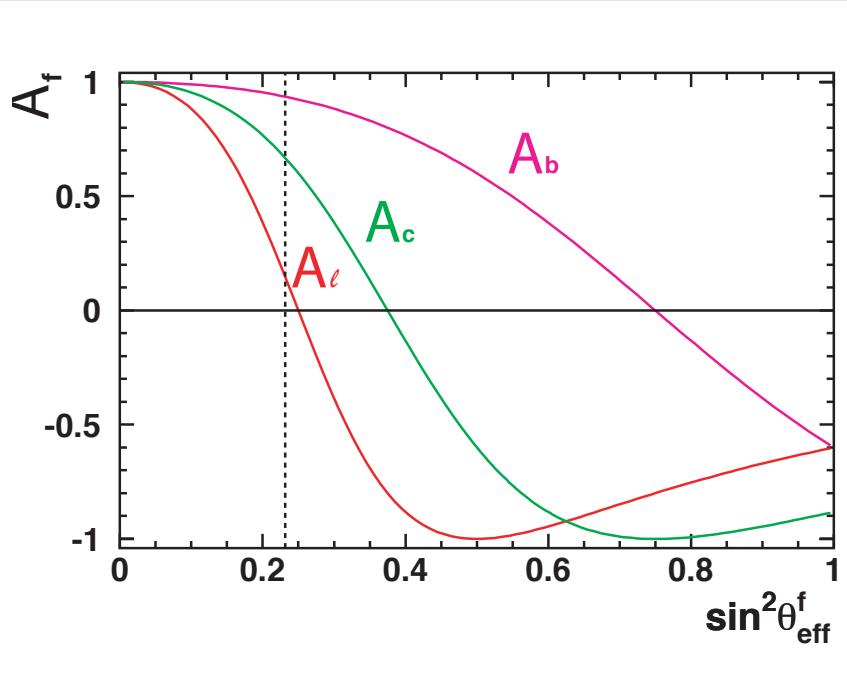
- Forward-backward asymmetries: $A_{\text{FB}}^f = \frac{N_F - N_B}{N_F + N_B}$, $A_{\text{FB}}^{0,f} = \frac{3}{4} A_e A_f$
- LEP measurements: $A_{\text{FB}}^{0,I}$, $A_{\text{FB}}^{0,c}$, $A_{\text{FB}}^{0,b}$

Via *IS polarisation (SLC)*: $A_{\text{LR}} = \frac{N_L - N_R}{N_L + N_R} \frac{1}{\langle |P|_e \rangle}$, $A_{\text{LRFB}} = \frac{(N_F - N_B)_L - (N_F - N_B)_R}{(N_F + N_B)_L + (N_F + N_B)_R} \frac{1}{\langle |P_e| \rangle}$

- Left-right, and left-right forward-backward asymmetries: $A_{\text{LR}}^0 = A_e$, $A_{\text{LRFB}}^{0,f} = \frac{3}{4} A_f$

Asymmetry and
Distinguish vector
Convenient to us

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2}$$



ings

on

i.e., $\sin^2 \theta_{\text{eff}}^f$)

$$\frac{\text{Re}(g_{V,f})}{\text{Re}(g_{A,f})} = 1 - 4 |Q_f| \sin^2 \theta_{\text{eff}}^f$$

Via final state (FS) angular distribution in unpolarised scattering (LEP)

- Forward-backward asymmetries: $A_{\text{FB}}^f = \frac{N_F - N_B}{N_F + N_B}$, $A_{\text{FB}}^{0,f} = \frac{3}{4} A_e A_f$
- LEP measurements: $A_{\text{FB}}^{0,I}$, $A_{\text{FB}}^{0,c}$, $A_{\text{FB}}^{0,b}$

Via IS polarisation (SLC): $A_{\text{LR}} = \frac{N_L - N_R}{N_L + N_R} \frac{1}{\langle |P|_e \rangle}$, $A_{\text{LRFB}} = \frac{(N_F - N_B)_L - (N_F - N_B)_R}{(N_F + N_B)_L + (N_F + N_B)_R} \frac{1}{\langle |P_e| \rangle}$

- Left-right, and left-right forward-backward asymmetries: $A_{\text{LR}}^0 = A_e$, $A_{\text{LRFB}}^{0,f} = \frac{3}{4} A_f$

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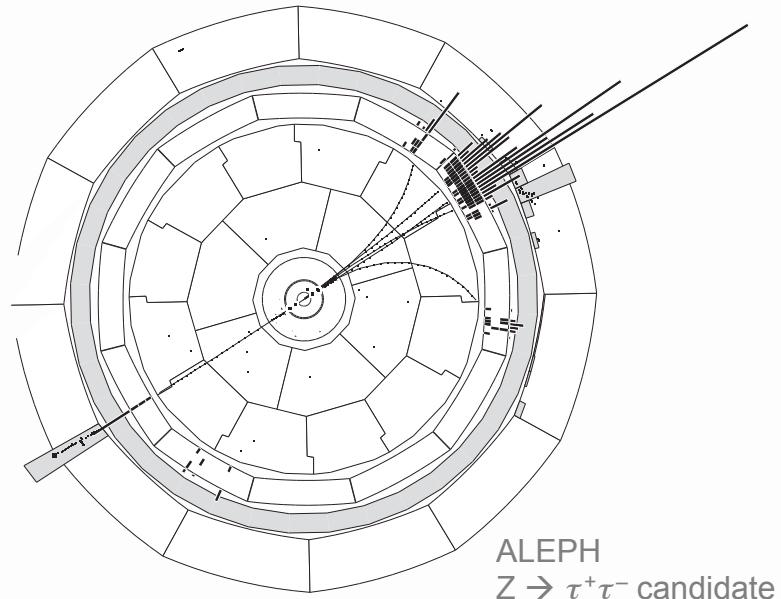
dependent on $\sin^2\theta_{\text{eff}}^f$: $\frac{\text{Re}(g_{V,f})}{\text{Re}(g_{A,f})} = 1 - 4|Q_f|\sin^2\theta_{\text{eff}}^f$

Via final state polarisation (LEP):

- Tau polarisation:

$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_\tau A_e\cos\theta}$$

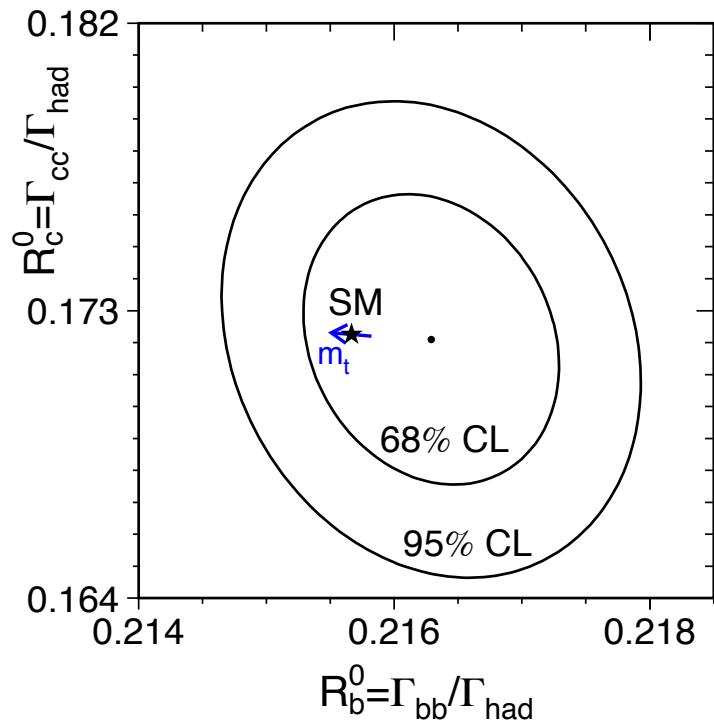
- Measure τ spin versus from energy and angular correlations in τ decays
- Fit at LEP determines: A_τ, A_e



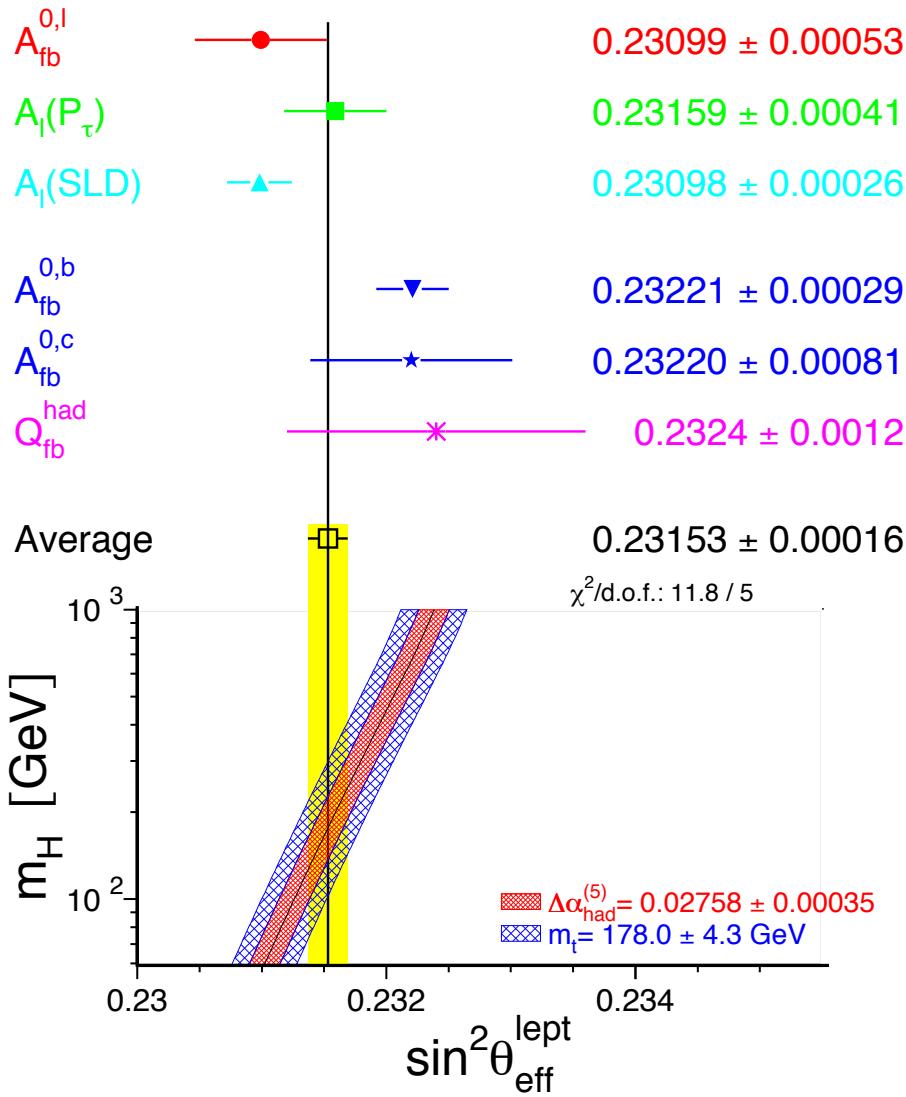
ALEPH
 $Z \rightarrow \tau^+\tau^-$ candidate

Heavy Flavour Measurements

- b and c quarks can be identified efficiently by LEP / SLD $\rightarrow R_b, R_c$
 - Especially R_b is sensitive to new physics connected to tb couplings
[With the m_t from the Tevatron the interest from SM is minor]
 - SLC measures in addition the asymmetry parameters A_b, A_c
 - These parameters are only sensitive to new physics at Born level
- Hence, these and the LEP $A_{FB}^{b/c}$ measurements cleanly determine $\sin^2\theta_{\text{eff}}$



Summary $\sin^2\theta_{\text{eff}}$ Measurements

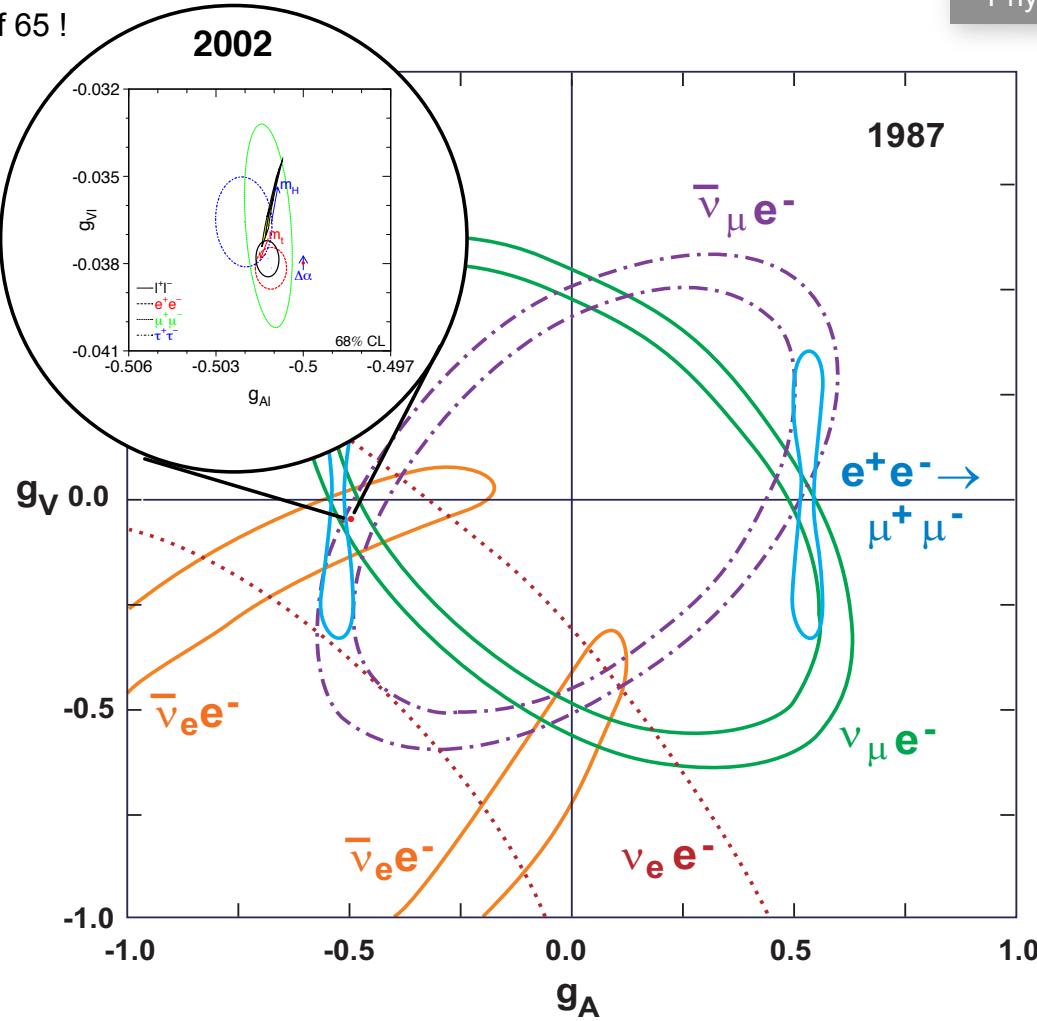


- Very precise measurement !
- Average dominated by $A_{\text{LR}}(\text{SLD})$ and A_{FB}^b
... which agree marginally only
(3.2σ , but overall average
 $\chi^2 = 11.8 / 5 \text{ dof} \rightarrow 2.0 \sigma$)
- In absence of convincing physics explanation, assume it is fluctuation

Neutral Current Couplings Before / After LEP

Inset expanded
by factor of 65 !

Combined paper LEP + SLC:
Phys. Rept. 427, 257 (2006)



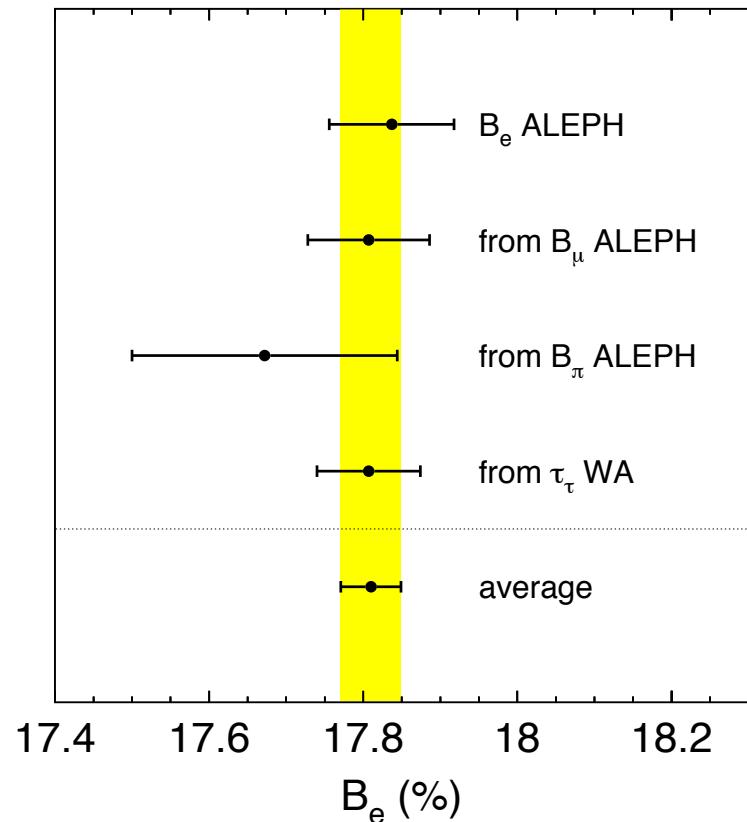
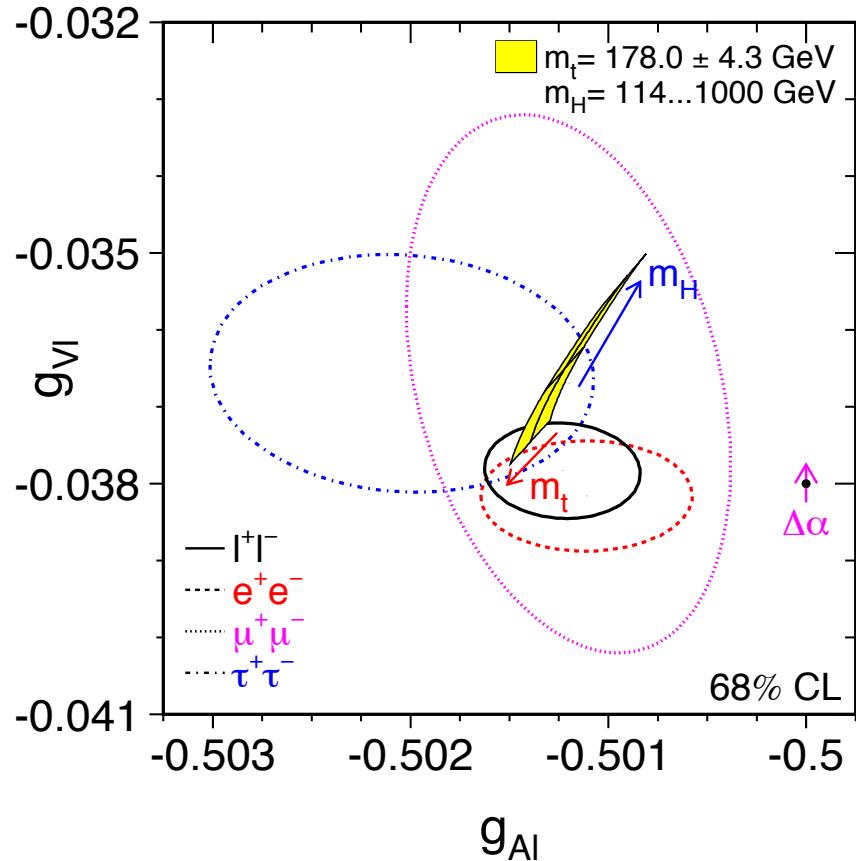
Status 1987:
Neutrino scattering and
 e^+e^- annihilation data
constrained the values of
 $g_{V\ell}$ and $g_{A\ell}$ to lie within
broad bands

Sensitive Tests of Lepton Universality

Universality of lepton couplings tested
at per-mil level

Combined paper LEP + SLC:
Phys. Rept. 427, 257 (2006)

ALEPH Tau report:
Phys. Rept. 421, 191 (2005)



Beyond the Z Pole

III CERN SL 02-08-99 11:26:44
LEP Run 6032 data of: 02-08-99 11:26:34
-** STABLE BEAMS **- (*)

$E = 100,010 \text{ GeV}/c$ Beam In Coast: 0.1
Beams e⁺ e⁻
 $I(t) \mu\text{A}$ 2040.6 2345.9
 $\tau_{au(t)} \text{ h}$ 6.30 7.36

LUMINOSITIES	L3	ALEPH	OPAL	DELPHI
$L(t) \text{ cm}^{-2}\text{s}^{-1}$	53.5	51.4	55.6	45.0
$/L(t) \text{ nb}^{-1}$	11.5	11.0	8.7	12.2
Bkg 1	0.80	1.21	0.00	1.02
Bkg 2	0.86	0.53	0.96	2.28

COMMENTS 02-08-99 11:26
COLLIMATORS AT PHYSICS SETTINGS

FIRST PHYSICS AT 100 GEV
WHAT ABOUT THAT???

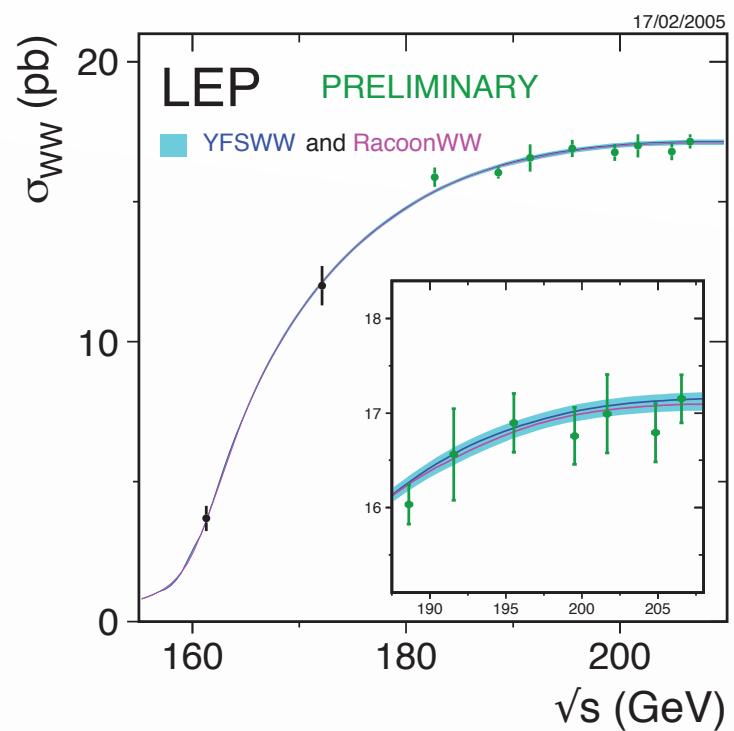
LEP1 page in August 2, 1999, 11:15
after reaching 200 GeV CM energy

Precision Measurement of the W mass

Results from LEP-II:

- 10 pb $^{-1}$ per experiment recorded close to the WW threshold
 - ▶ M_W from σ_{WW} measurements
 - ▶ Much less precise result than kinematic W reconstruction (200 MeV statistical error)
- 700 pb $^{-1}$ per experiment above the threshold
 - ▶ M_W directly reconstructed from invariant mass of observed leptons (dominant) and jets
 - ▶ Large FSI (“colour reconnection”) systematics in hadronic channel (35 MeV)
 - ▶ Combination: $M_W = (80.376 \pm 0.025 \pm 0.022)$ GeV

4 \times 700 pb $^{-1}$ taken for $\sqrt{s} = 161\text{--}209$ GeV between 1996 and 2000 at LEP-II



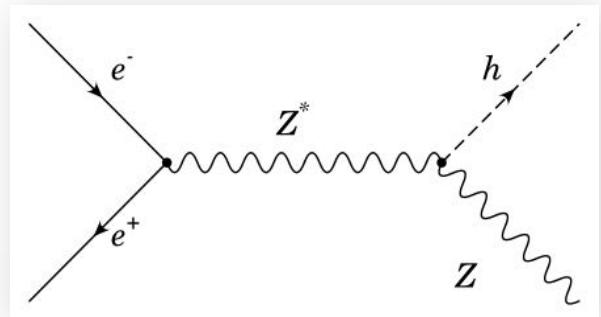
Results from Tevatron:

- Using leptonic W decays
 - ▶ M_W from template fits to the transverse mass or transverse momentum of lepton
 - ▶ Systematics dominated measurement (energy calibration), but reduced with better Z yield
 - ▶ Combination (2009): $M_W = (80.420 \pm 0.031)$ GeV

Direct Higgs Searches

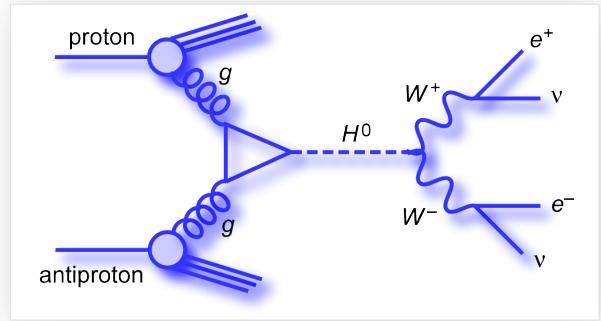
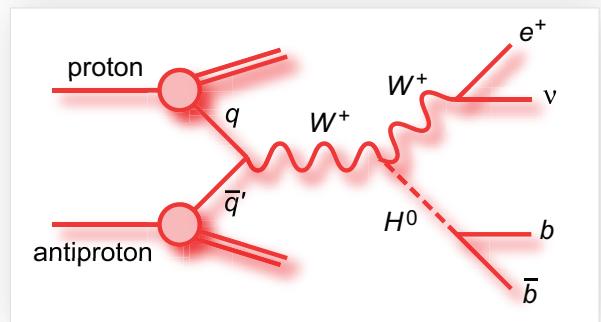
LEP-2: Higgs production via “Higgs-Strahlung”

- $e^- e^+ \rightarrow ZH (H \rightarrow bb, \tau\tau)$

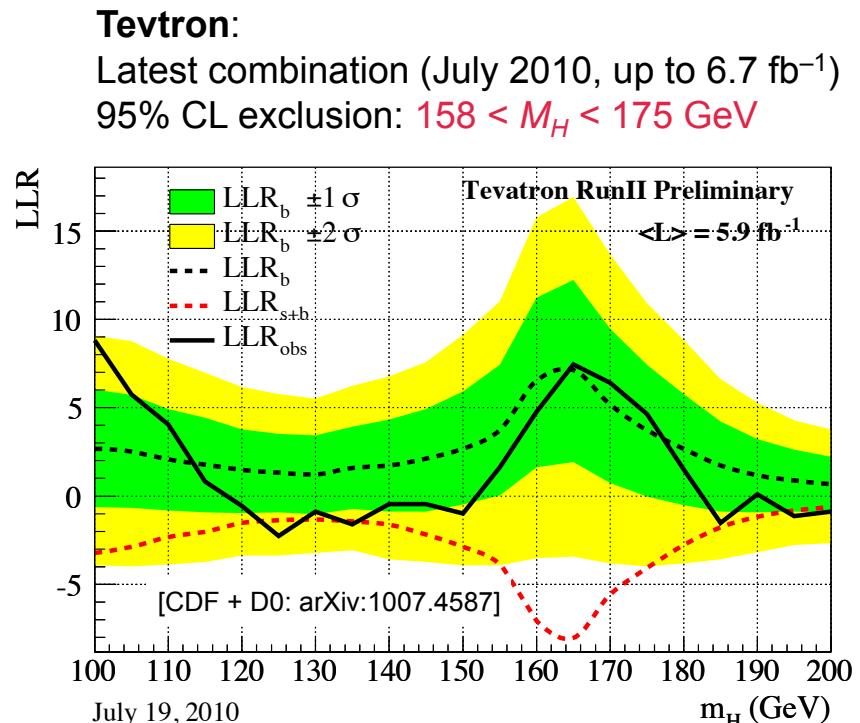
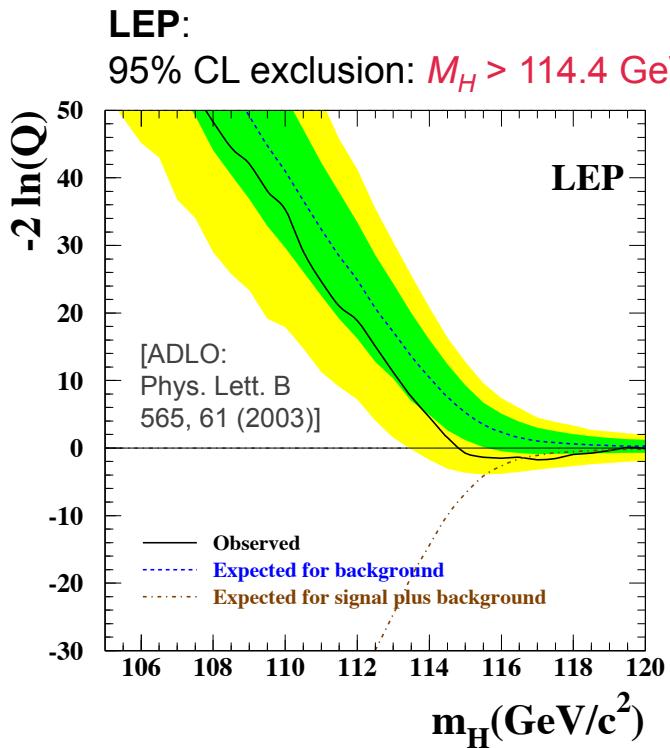


At Tevatron, armada of 90 mutually exclusive channels measured

- Low-mass ($M_H < 135$ GeV) searches dominated by WH associated production
- High-mass searches dominated by WW mode
- Massive use of high-end multivariate methods to boost performance
- Statistical combination of all the search channels
- Systematic uncertainties treated as nuisance parameters in combination and fit to data



Constraints from direct Higgs Searches



Statistical interpretation of limits: *two-sided CL_{s+b}*

- Experiments measure test statistics: $LLR = -2\ln Q$, where $Q = L_{s+b} / L_b$
- LLR is transformed by experiments into CL_{s+b}
- For SM fits, transform 1-sided CL_{s+b} into 2-sided CL_{s+b} : $\Delta\chi^2 = \text{Erf}^{-1}(1 - CL_{s+b}^{2\text{-sided}})$ (measure *deviation* from SM)
- Alternatively, use directly $\Delta\chi^2 \approx LLR$: Bayesian interpretation, lacks pseudo-MC information

Constraining the Higgs Mass...

... and other observables from the global fit to the electroweak data...

... by exploiting the precision measurements of radiative effects:

$$\rho_\ell = 1.0050 \pm 0.0010$$

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23153 \pm 0.00016$$

$$\Delta r = 0.0256 \pm 0.0014$$



All Observables Entering the Fit

Experimental results:

- **Z-pole observables**: LEP/SLD results (corrected for ISR/FSR QED effects)
[ADLO & SLD, Phys. Rept. 427, 257 (2006)]
 - **Total and partial cross sections** around Z: M_Z , Γ_Z , σ_{had}^0 , R_I^0 , R_c^0 , R_b^0
Sensitive to the total coupling strength of the Z to fermions
 - **Asymmetries** on the Z pole: $A_{\text{FB}}^{0,I}$, $A_{\text{FB}}^{0,b}$, $A_{\text{FB}}^{0,c}$, A_I , A_c , A_b , $\sin^2\theta_{\text{eff}}(Q_{\text{FB}})$
Sensitive to the ratio of the Z vector to axial-vector couplings (*i.e.* $\sin^2\theta_{\text{eff}}$) → parity violation
- M_W and Γ_W : LEP + Tevatron average
[ADLO, hep-ex/0612034] [CDF, Phys. Lett. 100, 071801 (2008)]
[CDF & D0, Phys. Rev. D 70, 092008 (2004)] [CDF & D0, arXiv:0908.1374v1]
- m_t : latest Tevatron average [CDF & D0, new combination for ICHEP 2010, arXiv:1007.3178]
- \bar{m}_c , \bar{m}_b : world averages [PDG, Phys. Lett. B667, 1 (2008) and 2009 partial update for the 2010 edition]
- $\Delta\alpha_{\text{had}}(M_Z)$: [DHMZ arXiv:1010.4180 (2010)] + rescaling mechanism to account for α_s dependency
- **Direct Higgs searches at LEP and Tevatron (ICHEP 2010 average)**
[ADLO: Phys. Lett. B565, 61 (2003)] [CDF & D0: arXiv:1007.4587 (2010)]

Experimental Input

Parameter	Input value
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ_{had}^0 [nb]	41.540 ± 0.037
R_ℓ^0	20.767 ± 0.025
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010
$A_\ell^{(*)}$	0.1499 ± 0.0018
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016
R_c^0	0.1721 ± 0.0030
R_b^0	0.21629 ± 0.00066
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012

LEP SLC LEP SLC

Parameter	Input value
M_H [GeV] ($^\circ$)	Confidence levels
M_W [GeV]	80.399 ± 0.023
Γ_W [GeV]	2.085 ± 0.042
\overline{m}_c [GeV]	$1.27^{+0.07}_{-0.11}$
\overline{m}_b [GeV]	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.3 ± 1.1
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ($\dagger\triangle$)	2749 ± 10
$\alpha_s(M_Z^2)$	—
$\delta_{\text{th}} M_W$ [MeV]	$[-4, 4]_{\text{theo}}$
$\delta_{\text{th}} \sin^2\theta_{\text{eff}}^\ell$ (\dagger)	$[-4.7, 4.7]_{\text{theo}}$
$\delta_{\text{th}} \rho_Z^f$ (\dagger)	$[-2, 2]_{\text{theo}}$
$\delta_{\text{th}} \kappa_Z^f$ (\dagger)	$[-2, 2]_{\text{theo}}$

LEP & Tevatron

Correlations for observables from Z lineshape fit

	M_Z	Γ_Z	σ_{had}^0	R_ℓ^0	$A_{\text{FB}}^{0,\ell}$
M_Z	1	-0.02	-0.05	0.03	0.06
Γ_Z		1	-0.30	0.00	0.00
σ_{had}^0			1	0.18	0.01
R_ℓ^0				1	-0.06
$A_{\text{FB}}^{0,\ell}$					1

Correlations for heavy-flavour observables at Z pole

	$A_{\text{FB}}^{0,c}$	$A_{\text{FB}}^{0,b}$	A_c	A_b	R_c^0	R_b^0
$A_{\text{FB}}^{0,c}$	1	0.15	0.04	-0.02	-0.06	0.07
$A_{\text{FB}}^{0,b}$		1	0.01	0.06	0.04	-0.10
A_c			1	0.11	-0.06	0.04
A_b				1	0.04	-0.08
R_c^0					1	-0.18

The Global Electroweak Fit

Theory predictions – state-of-the art calculations, in particular:

- M_W and $\sin^2\theta_{\text{eff}}^f$: full two-loop + leading beyond-two-loop form factor corrections
[M. Awramik et al., Phys. Rev D69, 053006 (2004) and ref.] [M. Awramik et al., JHEP 11, 048 (2006) and refs.]
- **Radiator functions**: 3NLO prediction of the massless QCD cross section
[P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]
- **Theoretical uncertainties**: M_W ($\delta_{\text{theo}}(M_H) = 4\text{--}6 \text{ GeV}$), $\sin^2\theta_{\text{eff}}^f$ ($\delta_{\text{theo}} = 4.7 \cdot 10^{-5}$)

Fit parameters

- In principle, **all parameters used in theory predictions are varying freely in fit**
- Masses of leptons and light quarks fixed to world-averages from PDG
- Free are running charm, bottom and top masses $\rightarrow m_t$ strongest impact on fit !



List of freely varying parameters in the SM fit:

$$\Delta\alpha_{\text{had}}^{(5)}(M_Z), \alpha_S(M_Z), M_Z, M_H, \bar{m}_c, \bar{m}_b, m_t$$

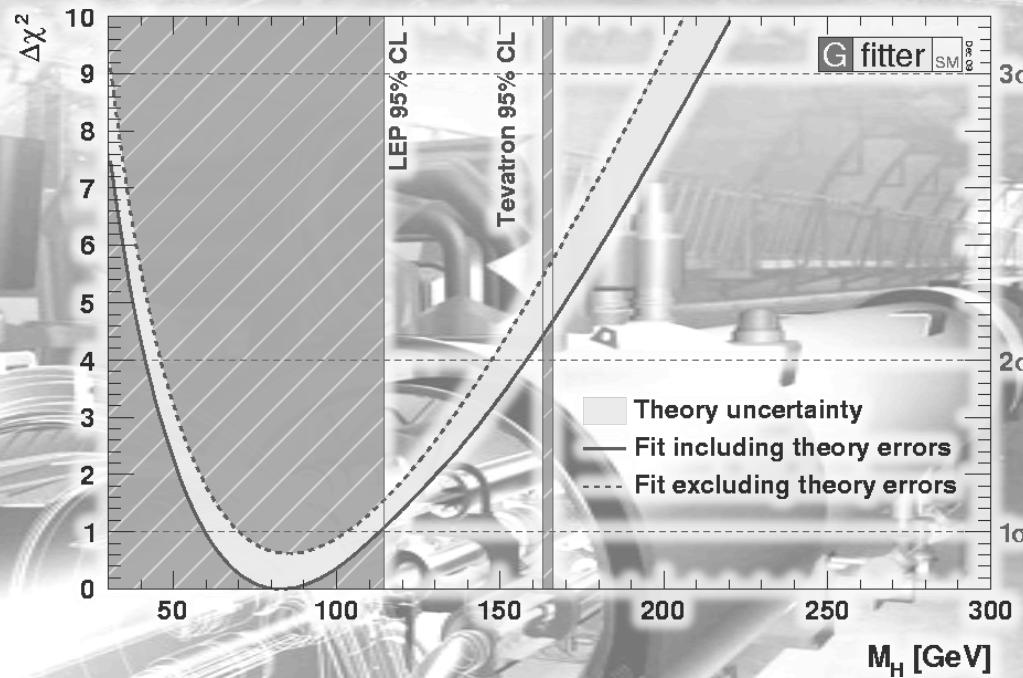
Fit Results^(*)

(*) Status: Nov 2010

Distinguish two fit types:

Standard Fit: all data except for direct Higgs searches

Complete Fit: all data including direct Higgs searches



Parameter	Input value	Free in fit	Results from global EW fits:		<i>Complete fit w/o exp. input in line</i>
			<i>Standard fit</i>	<i>Complete fit</i>	
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1942^{+0.0168}_{-0.0114}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4960 ± 0.0015	$2.4956^{+0.0015}_{-0.0014}$	$2.4952^{+0.0014}_{-0.0016}$
σ_{had}^0 [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.478 ± 0.014	41.469 ± 0.015
R_ℓ^0	20.767 ± 0.025	–	20.742 ± 0.018	$20.741^{+0.018}_{-0.017}$	20.718 ± 0.026
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	–	0.01641 ± 0.0002	$0.01625^{+0.0002}_{-0.0001}$	$0.01624^{+0.0002}_{-0.0001}$
$A_\ell^{(*)}$	0.1499 ± 0.0018	–	0.1479 ± 0.0010	$0.1472^{+0.0010}_{-0.0006}$	–
A_c	0.670 ± 0.027	–	$0.6683^{+0.00044}_{-0.00043}$	$0.6680^{+0.00042}_{-0.00027}$	$0.6679^{+0.00039}_{-0.00022}$
A_b	0.923 ± 0.020	–	0.93469 ± 0.00009	$0.93466^{+0.00005}_{-0.00008}$	$0.93466^{+0.00005}_{-0.00009}$
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	–	0.0741 ± 0.0005	$0.0738^{+0.0005}_{-0.0003}$	0.0739 ± 0.0004
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	–	0.1037 ± 0.0007	$0.1032^{+0.0007}_{-0.0004}$	$0.1036^{+0.0005}_{-0.0004}$
R_c^0	0.1721 ± 0.0030	–	0.17225 ± 0.00006	0.17225 ± 0.00006	0.17225 ± 0.00006
R_b^0	0.21629 ± 0.00066	–	$0.21578^{+0.00005}_{-0.00008}$	$0.21576^{+0.00007}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00008}$
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012	–	0.23141 ± 0.00012	$0.23150^{+0.00007}_{-0.00013}$	$0.23149^{+0.00008}_{-0.00011}$
M_H [GeV] (°)	Confidence levels	yes	$95.7^{+30.6[+75.8]}_{-24.2[-43.7]}$	$120.2^{+18.1[+35.1]}_{-4.7[-5.8]}$	$95.7^{+30.6[+75.8]}_{-24.2[-43.7]}$
M_W [GeV]	80.399 ± 0.023	–	$80.382^{+0.014}_{-0.015}$	80.370 ± 0.008	$80.360^{+0.016}_{-0.018}$
Γ_W [GeV]	2.085 ± 0.042	–	2.092 ± 0.001	2.092 ± 0.001	2.092 ± 0.001
\overline{m}_c [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
\overline{m}_b [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.16}_{-0.07}$	$4.20^{+0.16}_{-0.07}$	–
m_t [GeV]	173.3 ± 1.1	yes	173.4 ± 1.1	173.7 ± 1.0	$177.4^{+11.8}_{-3.5}$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ (†△)	2749 ± 10	yes	2750 ± 10	2748 ± 10	2729^{+39}_{-55}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$
$\delta_{\text{th}} M_W$ [MeV]	$[-4, 4]_{\text{theo}}$	yes	4	4	–
$\delta_{\text{th}} \sin^2\theta_{\text{eff}}^\ell$ (†)	$[-4.7, 4.7]_{\text{theo}}$	yes	4.7	4.7	–
$\delta_{\text{th}} \rho_Z^f$ (†)	$[-2, 2]_{\text{theo}}$	yes	2	2	–
$\delta_{\text{th}} \kappa_Z^f$ (†)	$[-2, 2]_{\text{theo}}$	yes	2	2	–

Correlation coefficients of free fit parameters

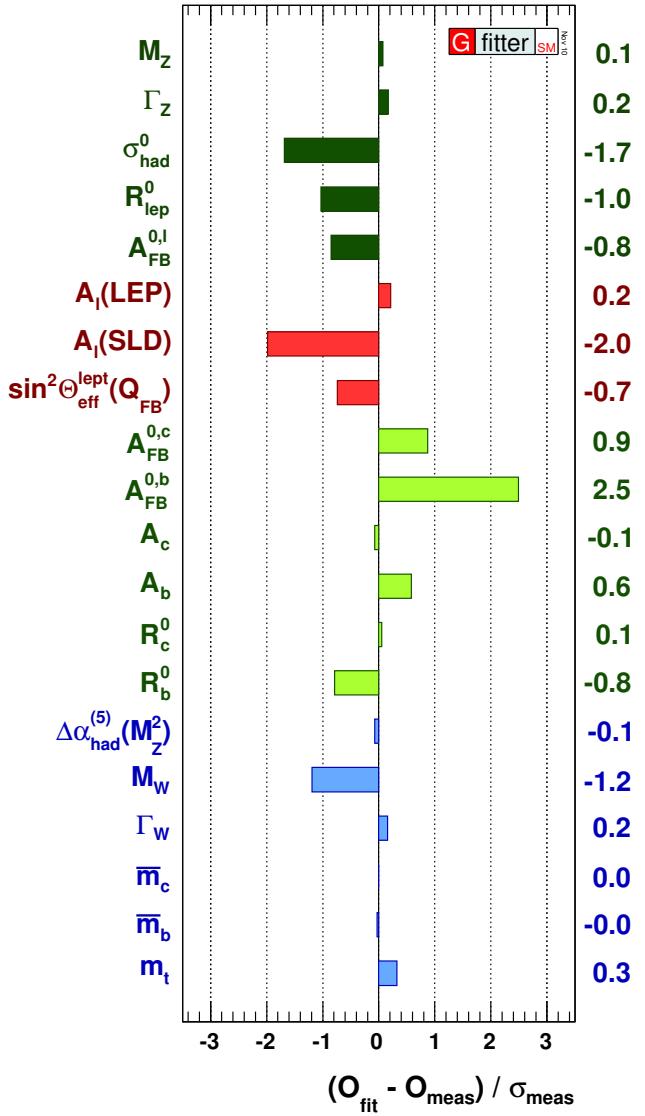
Goodness-of-Fit

Goodness-of-fit:

- Standard fit: $\chi^2_{\text{min}} = 16.6 \rightarrow \text{Prob}(\chi^2_{\text{min}}, 13) = 0.22$
- Complete fit: $\chi^2_{\text{min}} = 17.5 \rightarrow \text{Prob}(\chi^2_{\text{min}}, 14) = 0.24$
- ➡ *No requirement for new physics*

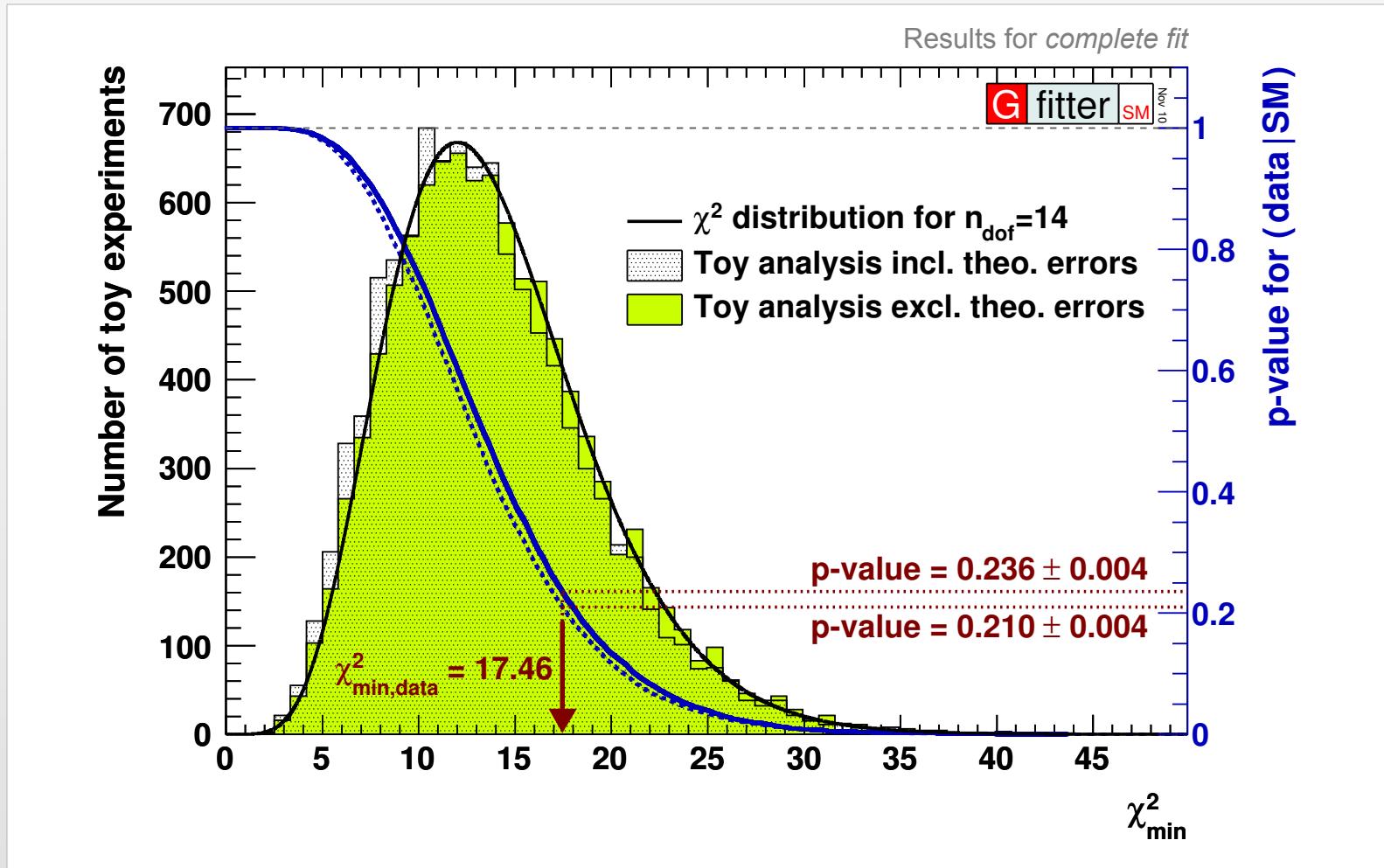
Pull values for complete fit (right figure →)

- No individual pull exceeds 3σ
- FB(b) asymmetry largest contributor to χ^2_{min}
- Small contributions from M_Z , $\Delta\alpha^{\text{had}}(M_Z)$, m_c , m_b indicate that their input accuracies exceed fit requirements → parameters could have been fixed in fit
- Can describe data with only two floating parameters (α_S , M_H)



Goodness-of-Fit

Toy analysis: p-value for wrongly rejecting the SM = $0.24 \pm 0.01\text{--}0.02_{\text{theo}}$

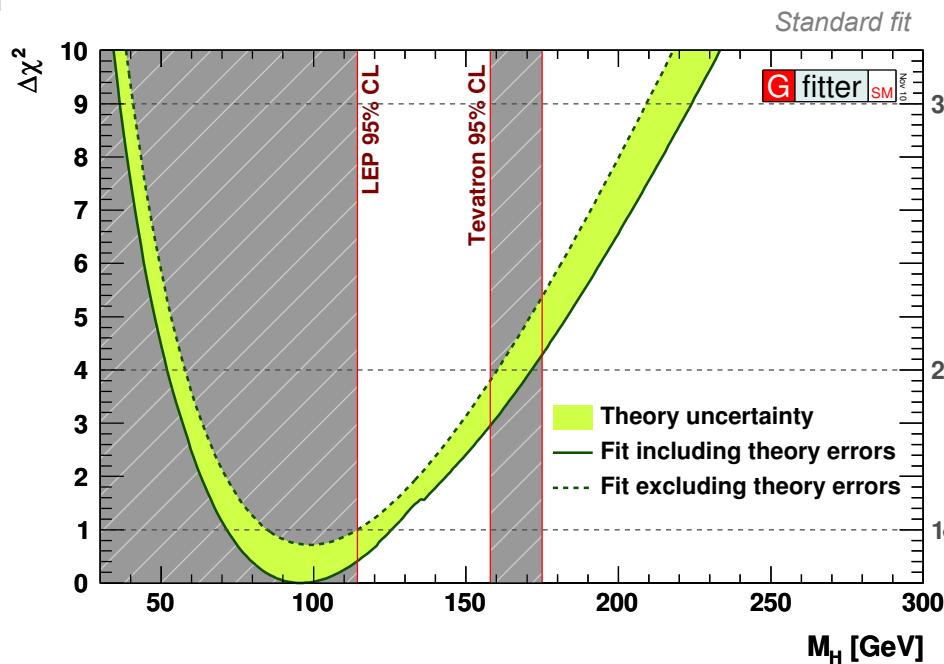


Higgs Mass Constraints

M_H from *Standard fit*:

- Central value $\pm 1\sigma$: $M_H = 96^{+30}_{-25}$ GeV
- 95% CL upper limit: 170 GeV

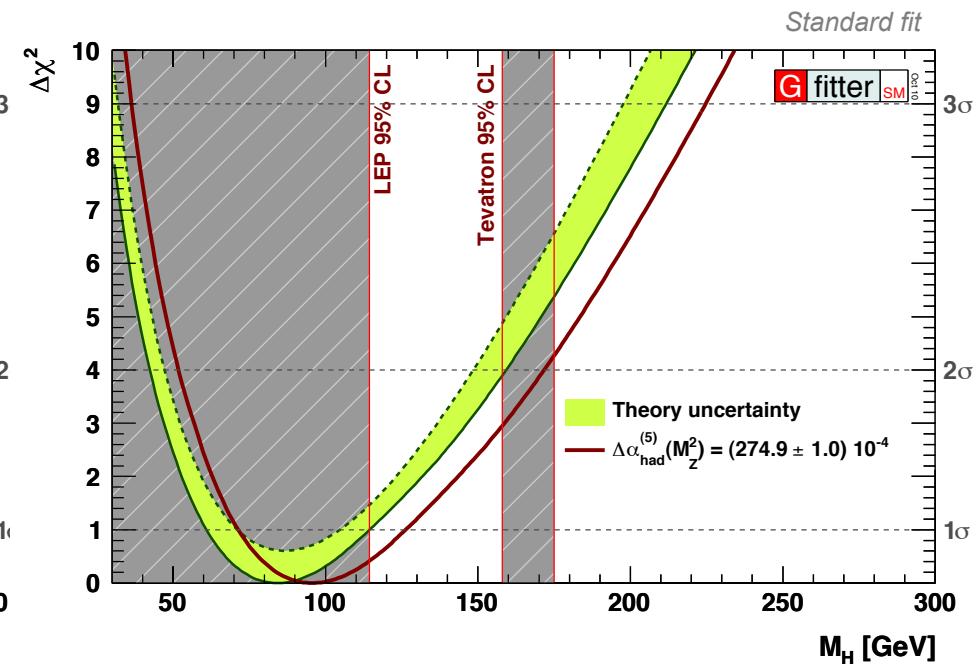
Green band due to *Rfit* treatment of theory errors, fixed errors lead to larger χ^2_{min}



M_H from *old Standard fit*:

- Central value $\pm 1\sigma$: $M_H = 90^{+30}_{-24}$ GeV
- 95% CL upper limit: 164 GeV

Illustrate effect from new $\Delta\alpha_{\text{had}}$ precision determination (reduced EM coupling !)



Higgs Mass Constraints

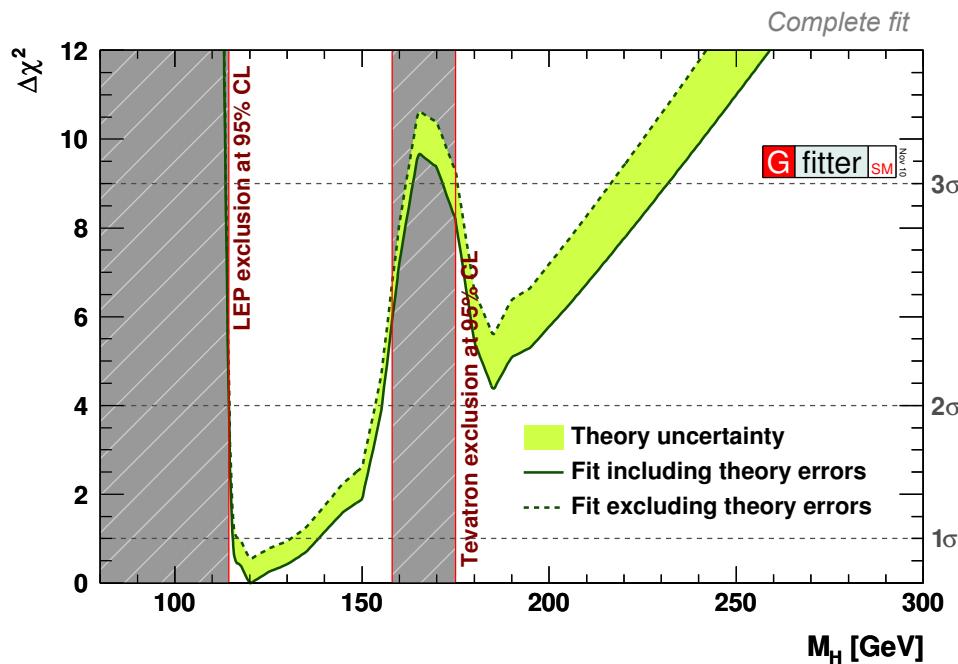
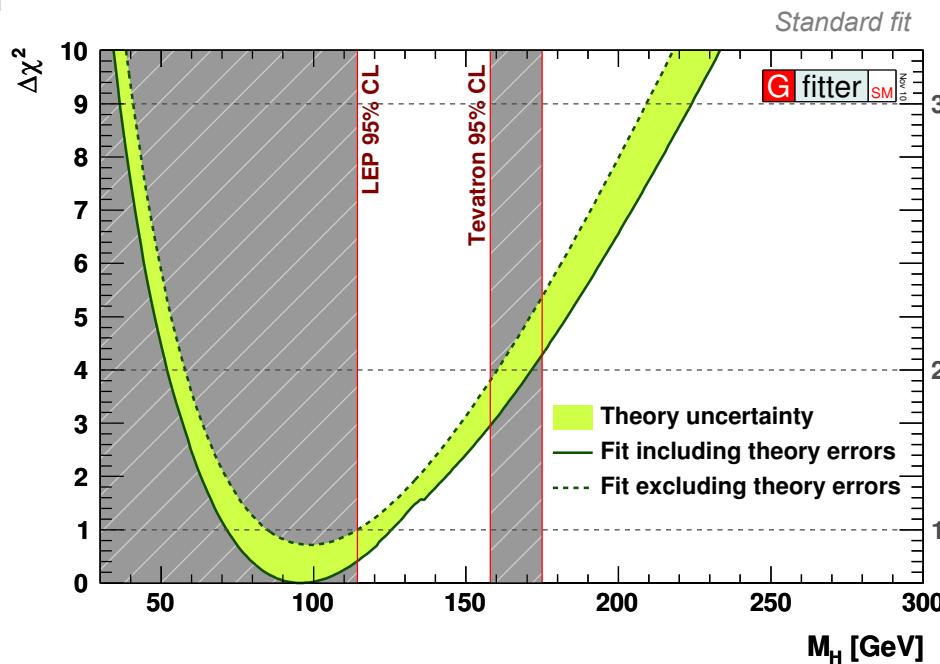
M_H from Standard fit:

- Central value $\pm 1\sigma$: $M_H = 96^{+30}_{-25}$ GeV
- 95% CL upper limit: 170 GeV

Green band due to *R*fit treatment of theory errors, fixed errors lead to larger χ^2_{min}

M_H from Complete fit:

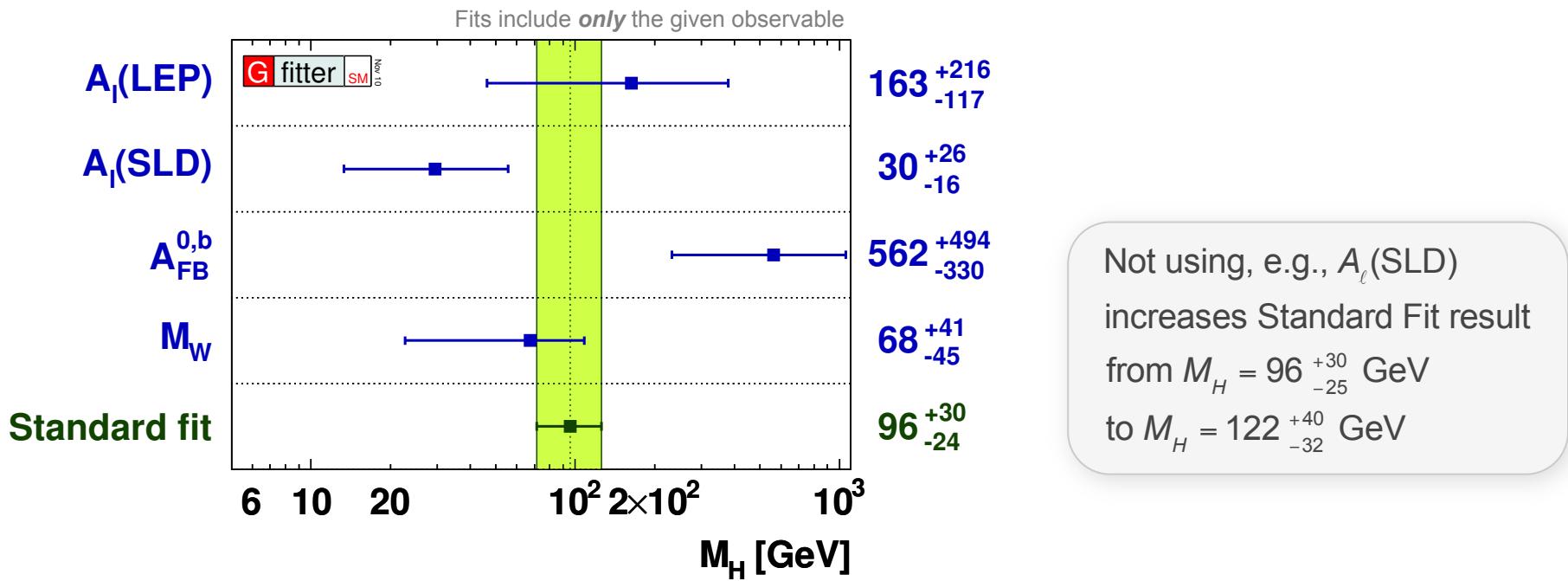
- Central value $\pm 1\sigma$: $M_H = 120^{+18}_{-5}$ GeV
- 95% CL upper limit: 155 GeV



Higgs Mass Constraints

Known tension between $A_{FB}^{0,b}$ and $A_{lep}(SLD)$ and M_W :

- Pseudo-MC analysis to evaluate
“Probability to observe a $\Delta\chi^2 = 8.0$ when removing the least compatible input”
→ accounts for “look-elsewhere effect”
- Find: 1.4% (2.5 σ)



Top Mass

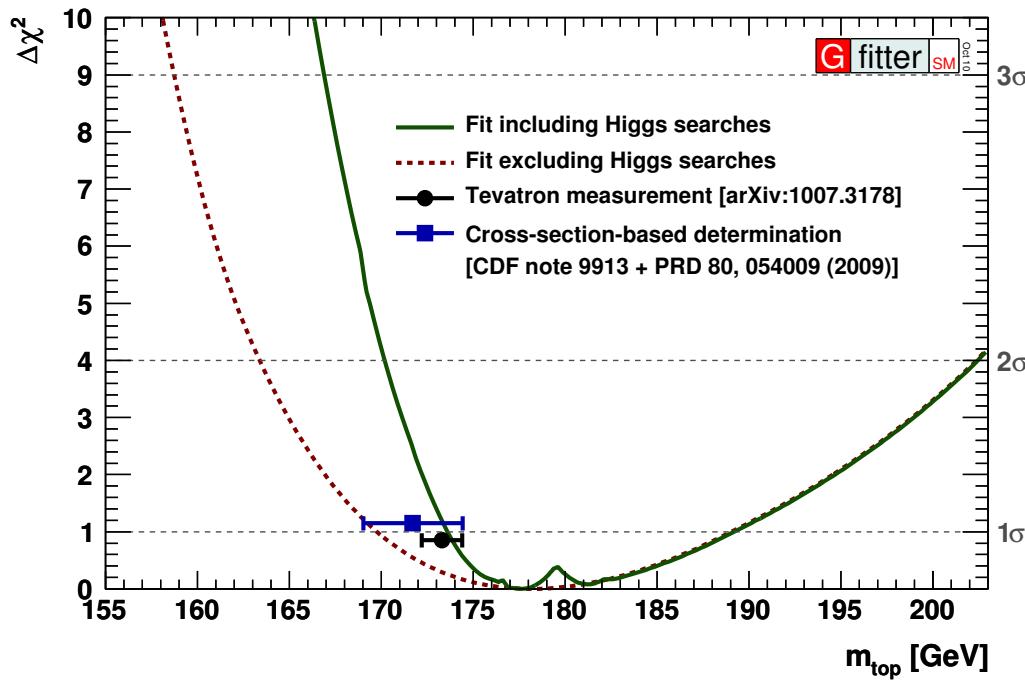
Quadratic sensitivity to m_{top}

- Complete fit: $m_{\text{top}} = 177.4^{+11.8}_{-3.5} \text{ GeV}$

Tevatron average: $(173.3 \pm 1.1) \text{ GeV}$

From cross section: $m_{\text{top}}^{\text{pole}} = (171.7^{+2.1}_{-2.0})_{\sigma_{t\bar{t}}} \pm 0.9_{\text{PDF}} \pm 1.5_{\mu} \text{ GeV}$

Unambiguously
defined observable!



Note: profile of the *standard fit* exhibits an asymmetry opposite to the naïve expectation from $\sim m_t^2$ dependence of loop corrections

Reason: floating Higgs mass and its positive correlation with m_t

Top Mass

Quadratic sensitivity to m_{top}

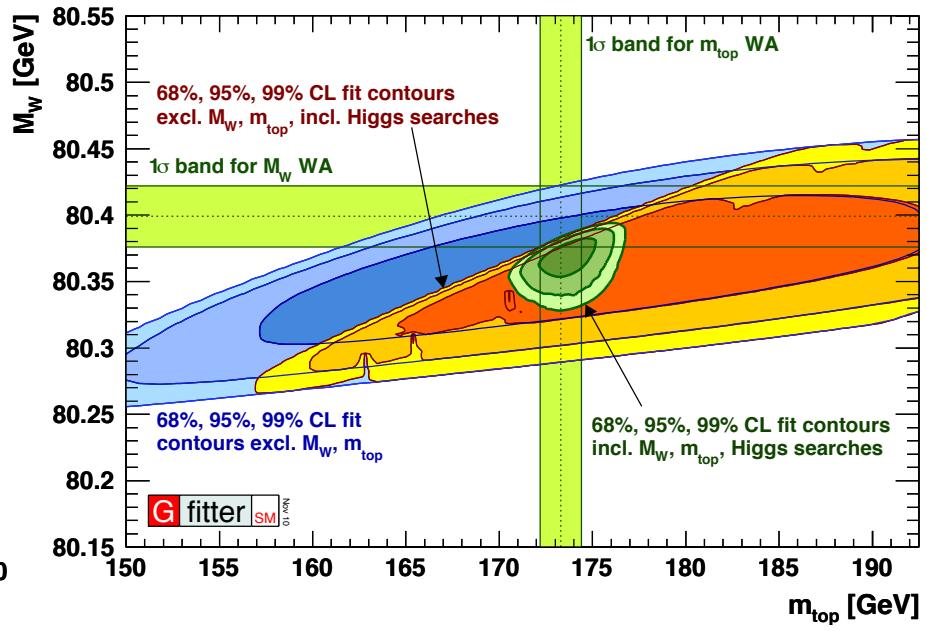
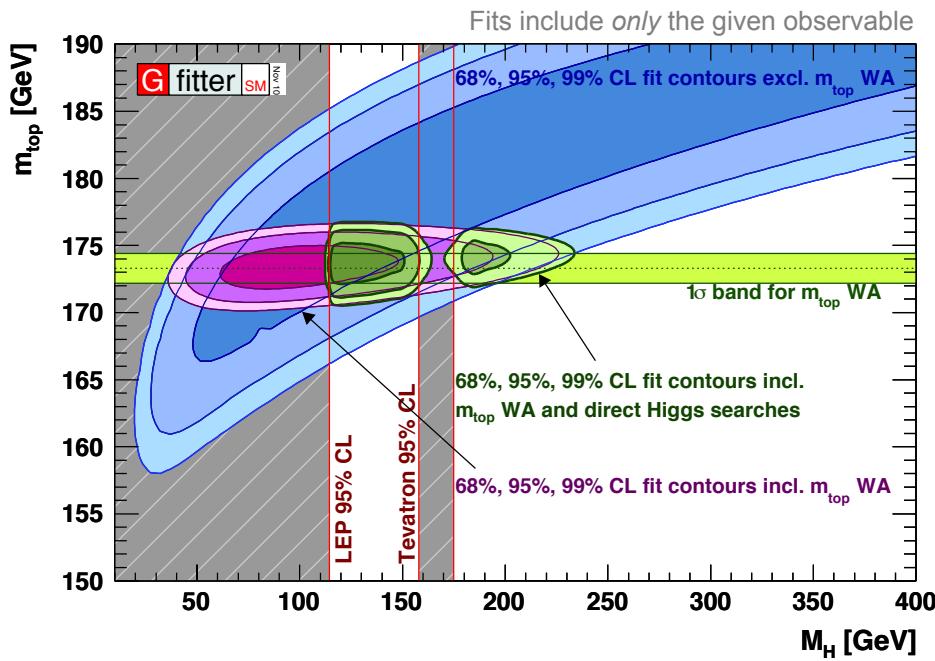
- Complete fit: $m_{\text{top}} = 177.4^{+11.8}_{-3.5}$ GeV

Tevatron average: (173.3 ± 1.1) GeV

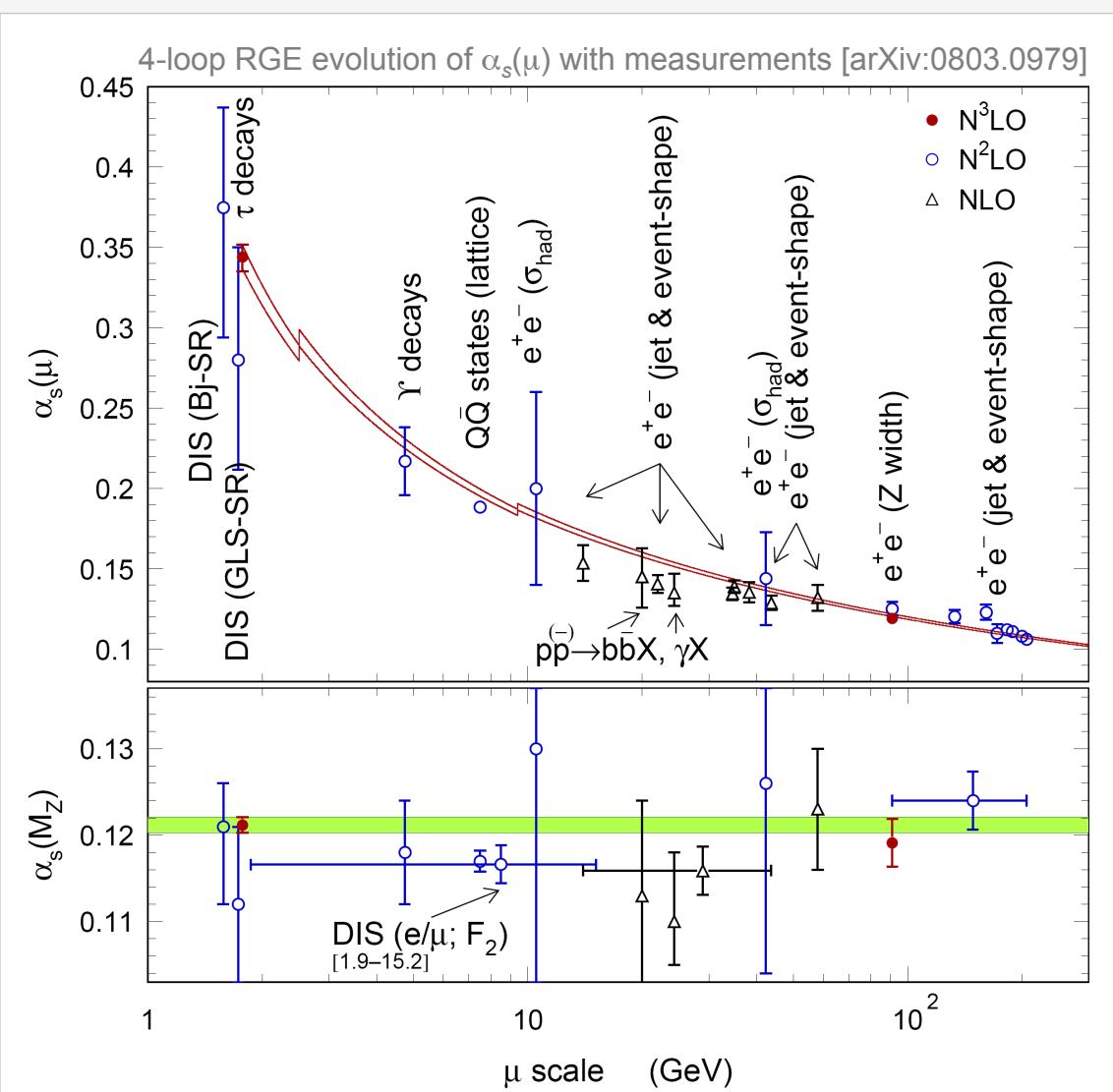
Fit (i.e. excluding the Higgs searches and the respective measurements)

Fit + Higgs searches

Fit + Higgs searches + direct measurements
→ best knowledge of SM



3NLO Determination of α_s



From Complete Fit:

$$\alpha_s(M_Z) = 0.1193 \pm 0.0028 \pm 0.0001$$

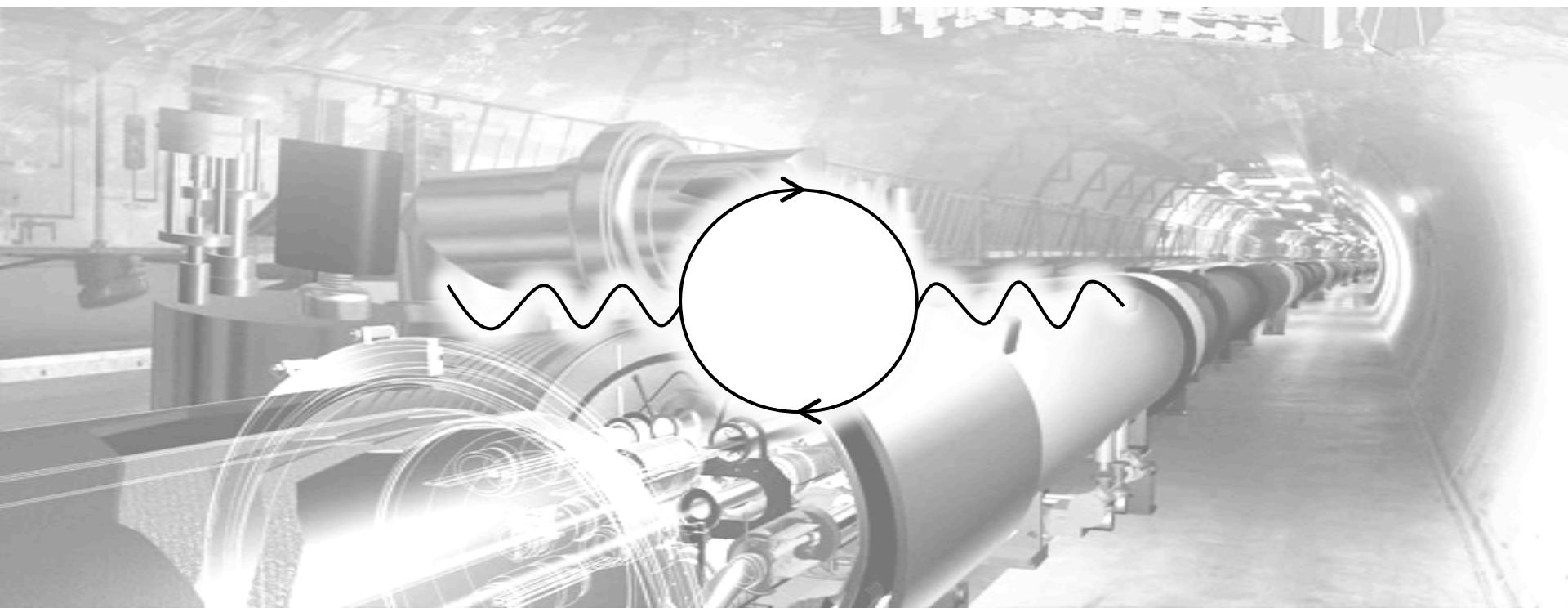
- First error experimental
- Second error theoretical (!)

[incl. variation of renorm. scale from $M_Z/2$ to $2M_Z$ and massless terms of order/beyond $\alpha_s^5(M_Z)$ and massive terms of order/beyond $\alpha_s^4(M_Z)$]
- Excellent agreement with N^3LO result from hadronic τ decays

[M. Davier et al., arXiv:0803.0979]
- Best current test of asymptotic freedom property of QCD !

Electroweak Precision Data and Constraints Beyond the SM

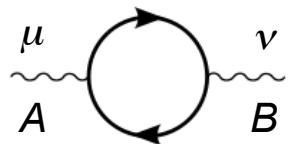
“Oblique Corrections”



Oblique Corrections

At low energies, BSM physics appears dominantly through vacuum polarisation

- Aka, *oblique corrections*

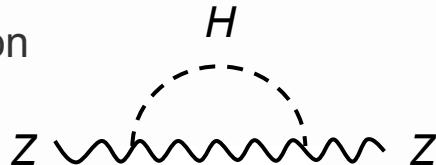

$$= i\Pi_{AB=\{W,Z,\gamma\}}^{\mu\nu}(q)$$

- Direct corrections (vertex, box, bremsstrahlung) generally suppressed by m_f / Λ

Oblique corrections reabsorbed into electroweak parameters $\Delta\rho$, $\Delta\kappa$, Δr

Electroweak fit sensitive to BSM physics through oblique corrections

- In direct competition with Higgs loop corrections



- Oblique corrections from New Physics described through **STU parameters**

[Peskin-Takeuchi, Phys. Rev. D46, 381 (1992)]

$$O_{\text{meas}} = O_{\text{SM,ref}}(M_H, m_t) + c_S S + c_T T + c_U U$$

S: (*S+U*) New Physics contributions to neutral (charged) currents

T: Difference between neutral and charged current processes – sensitive to weak isospin violation

U: Constrained by M_W and Γ_W . Usually very small in NP models (often: $U=0$)

The Oblique Parameters in the Standard Model

STU references in SM obtained from fit to EW observables

- SM_{ref} chosen at:
 $M_H = 120 \text{ GeV}$ and $m_t = 173.1 \text{ GeV}$
- This defines $(S, T, U) = (0, 0, 0)$



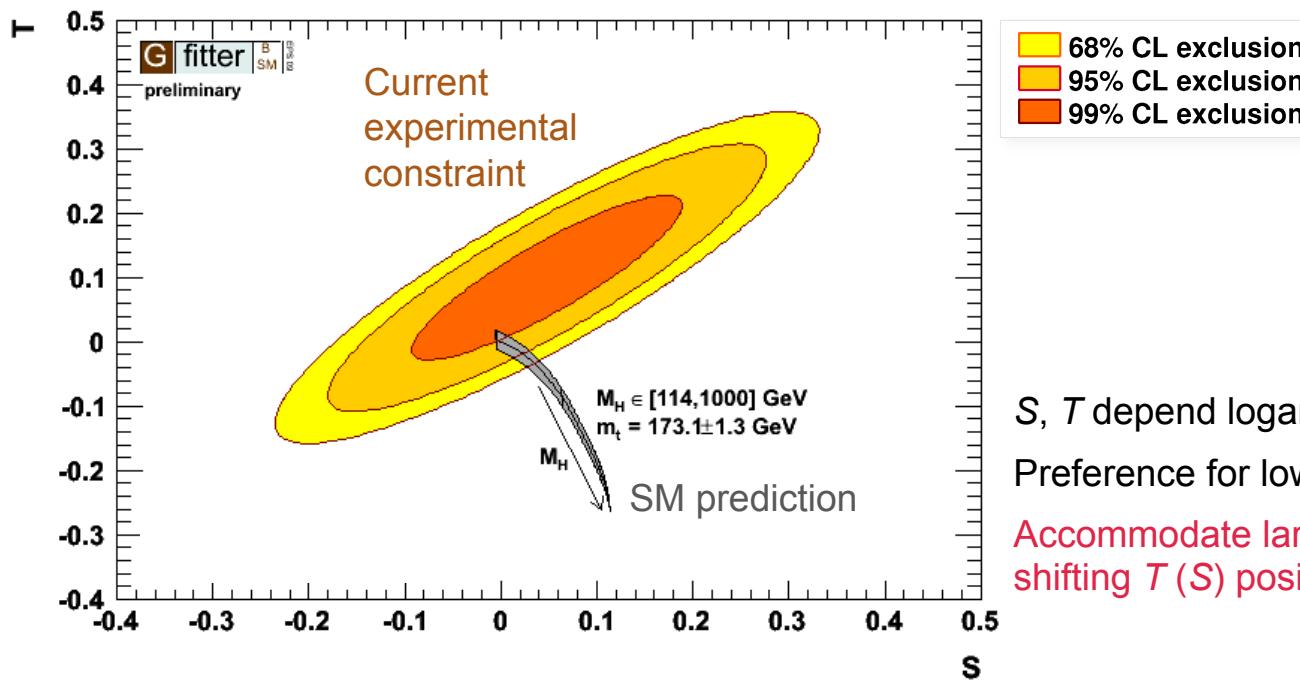
Results from Standard Model fit:

$$S = 0.02 \pm 0.11$$

$$T = 0.05 \pm 0.12$$

$$U = 0.07 \pm 0.12$$

	S	T	U
S	1	0.88	-0.47
T		1	-0.72
U			1



S, T depend logarithmically on M_H

Preference for low M_H values

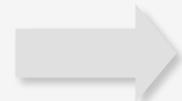
Accommodate large M_H values by shifting T (S) positive (negative)

Little Higgs Models (LHM)

STU predictions (oblique corrections)
inserted for Littlest Higgs model

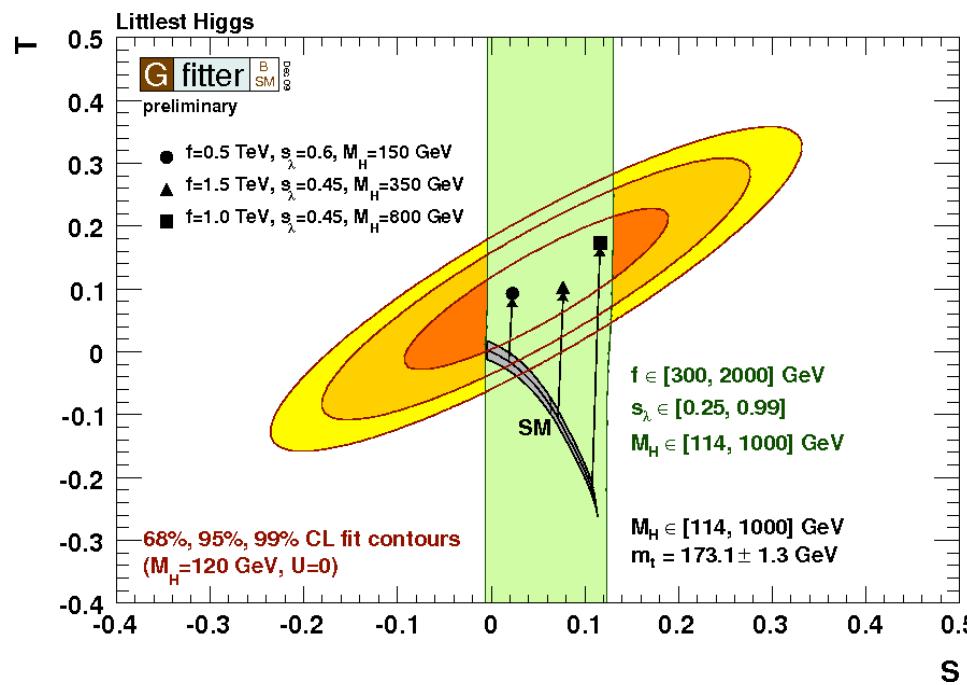
[Hubisz et al., JHEP 0601:135 (2006)]

Parameters of LH model:



- f : symmetry breaking scale (new particles)
- $s_\lambda \equiv m_{T_-} / m_{T_+}$
- Coefficient δ_c – depends on detail of UV physics.
Treated as theory uncertainty in fit: $\delta_c = [-5, 5]$
- F : degree of finetuning

Results: **Large f** : LH approaches SM and SM M_H constraints. **Smaller f** : M_H can be large.
Due to strong s_λ dependence, no absolute exclusion limit



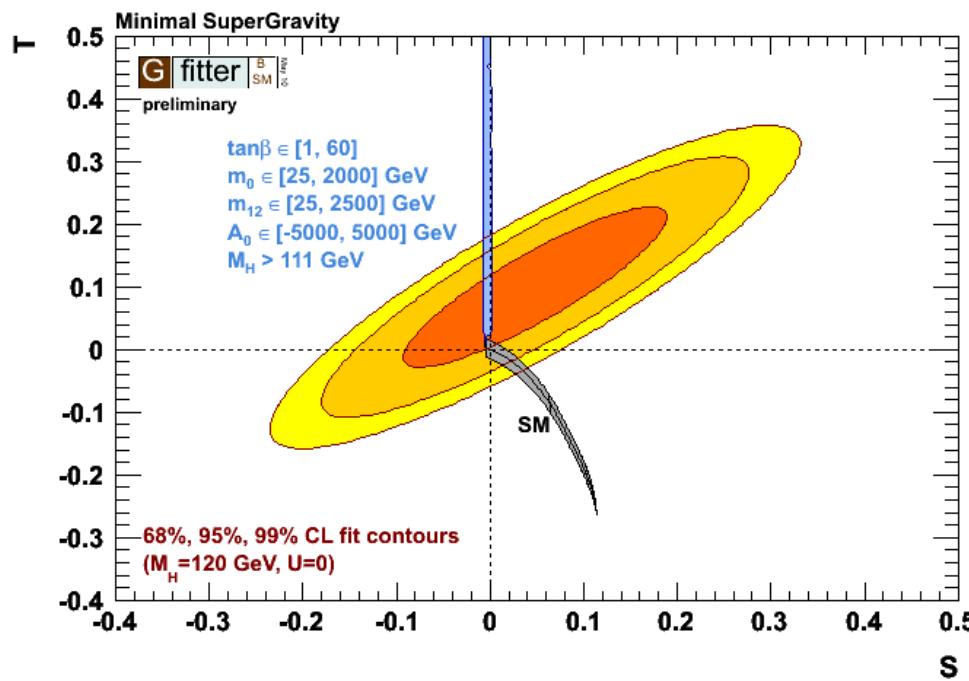
MSSM (SUSY) with mSUGRA

mSUGRA: highly constrained SUSY breaking mechanism at GUT scale, determined by 5 parameters:

- $m_{1/2}$, m_0 – fermion/scalar masses at GUT scale
- $\tan\beta$ – ratio of two Higgs vev's
- A_0 – trilinear coupling of Higgs
- $\text{sgn}(\mu)$ – sign of Higgsino mass term

- Oblique corrections dominated by weak isospin violation in: $m_{\tilde{b}_1}$, $m_{\tilde{t}_1}$, and $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$
- By construction of the oblique parameters
→ T parameter has dominant contribution

Fits use external code interfaced to Gfitter:
FeynHiggs, MicrOMEGAs, SuperIso, SOFTSUSY



Fourth Fermion Generation

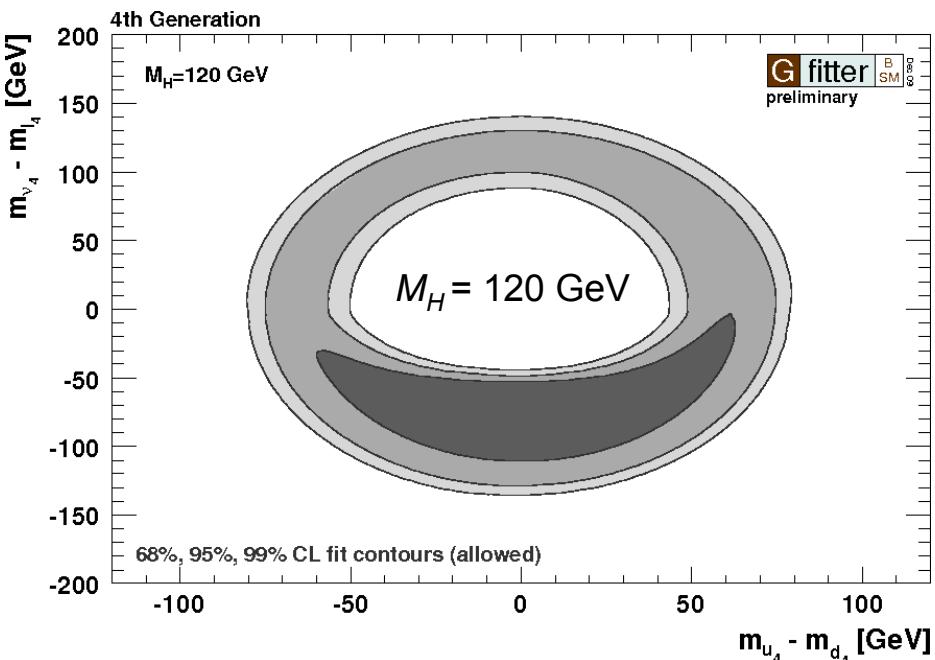
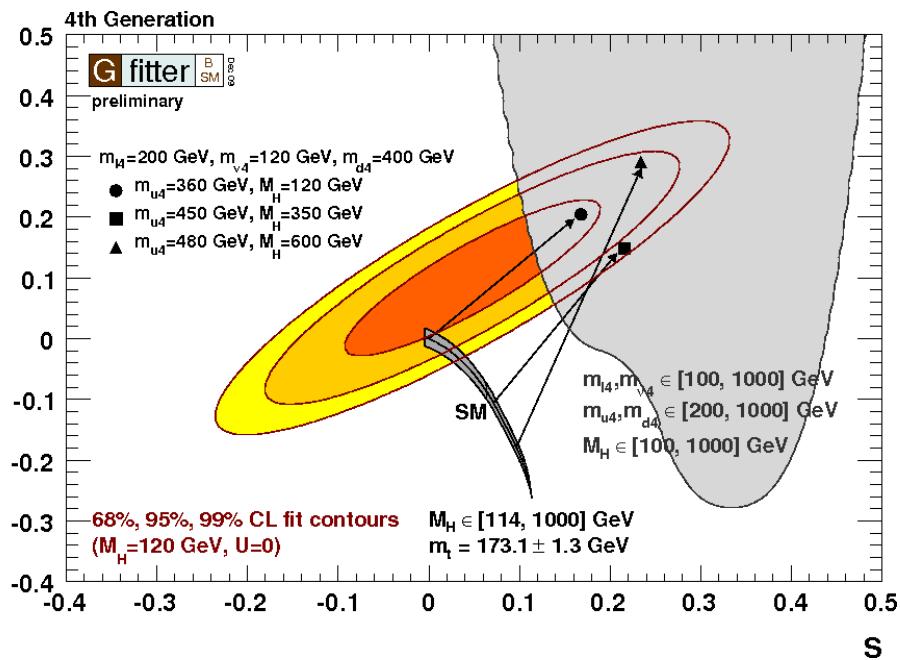
Introduce new lepton and quark states

Free parameters: m_{u_4} , m_{d_4} , m_{e_4} , m_{ν_4}

- Assume: no mixing of extra fermions
- Shift $\Delta S \approx 0.21$ from heavy generation
- Sensitive to mass difference between up- and down-type fields (not to absolute mass scale)

Results:

- With appropriate mass differences: fourth fermion model consistent with EW data
 - In particular a large M_H is allowed
- 5+ generations disfavored
- Data prefer a heavier charged lepton / up-type quark (which both reduce size of S)



Fourth Fermion Generation

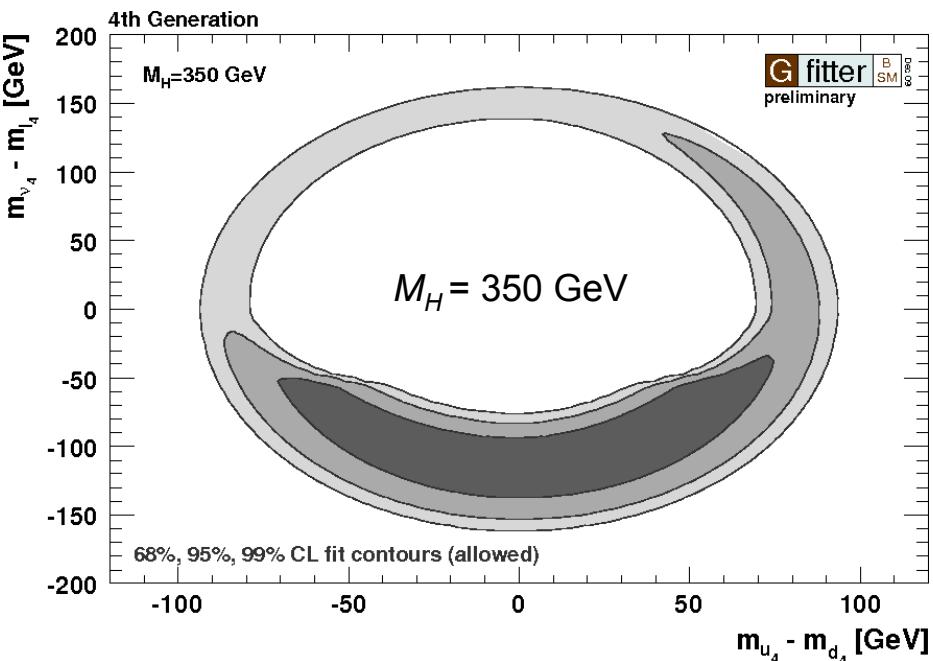
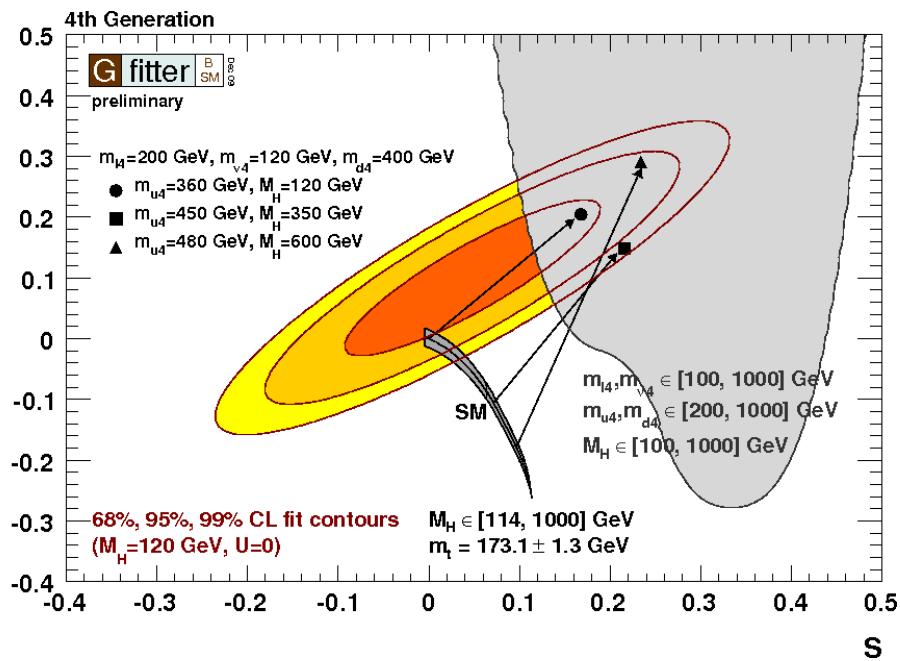
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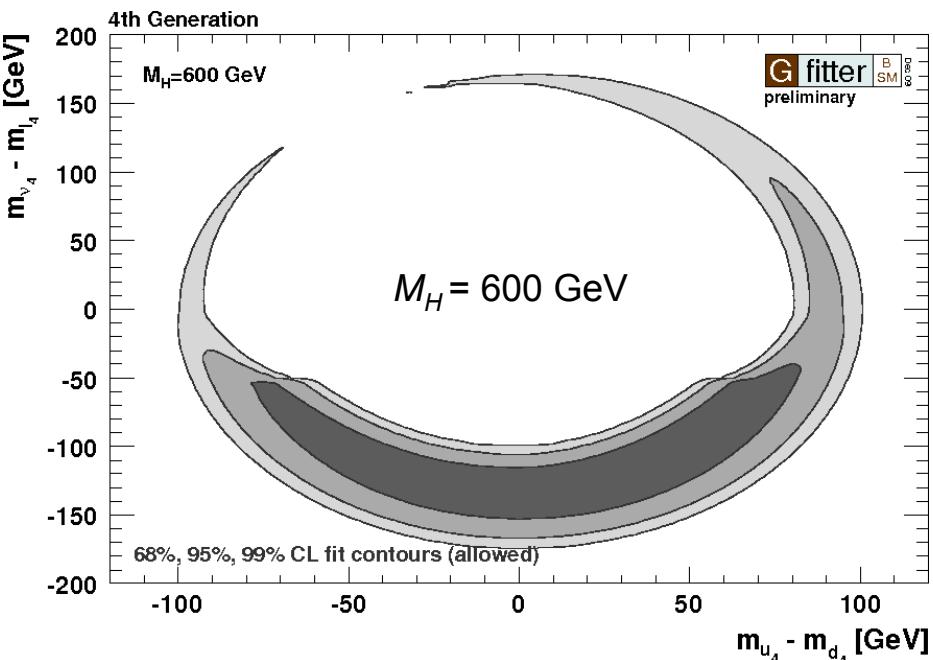
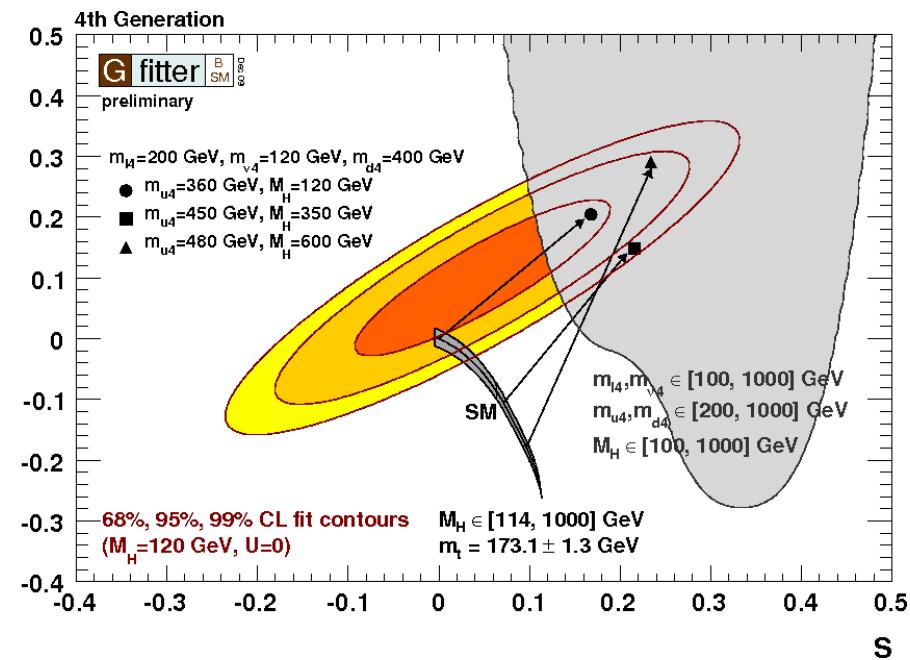
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Universal Extra Dimensions (UED)

All SM particles can propagate into ED

Compactification \rightarrow KK excitations

Conserved KK parity (LKK is DM candidate)

Model parameters:

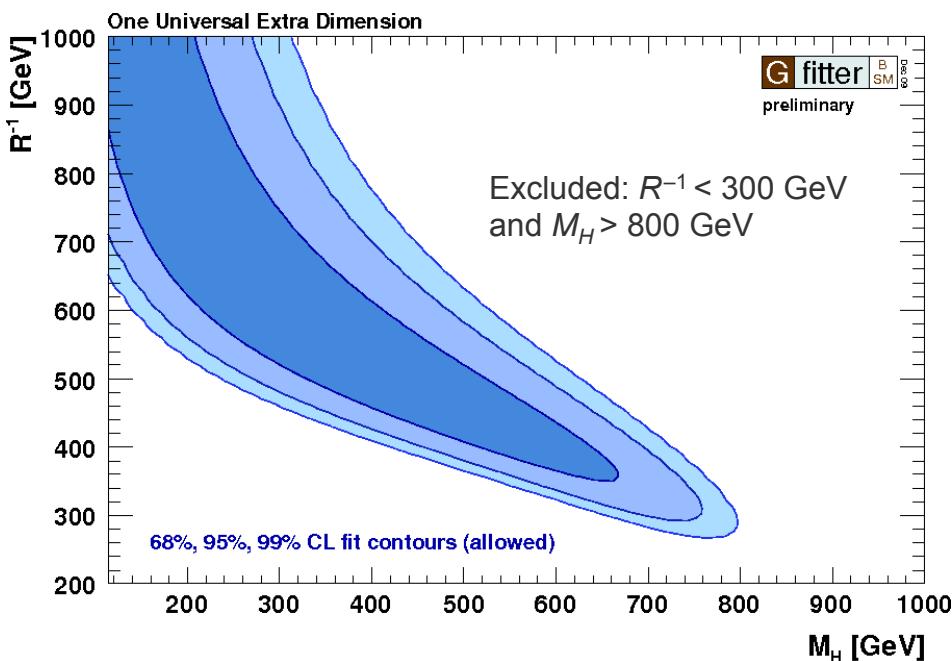
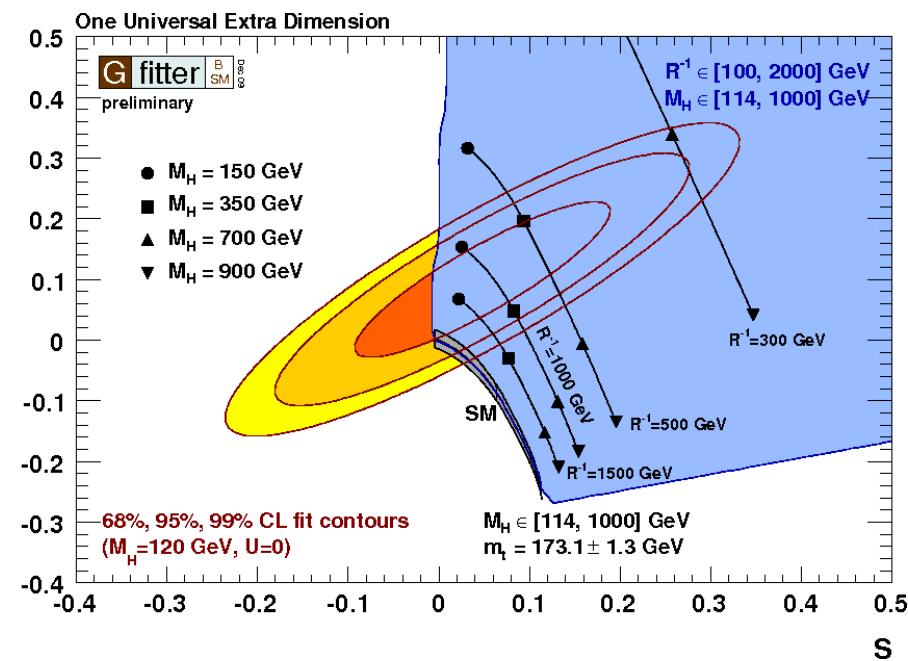
- d_{ED} : number of ED (fixed to $d_{ED}=1$)
- R^{-1} : compactification scale ($m_{KK} \sim n/R$)

Contribution to oblique parameters:

- From KK-top/bottom and KK-Higgs loops

Results:

- Large R^{-1} : UED approaches SM (exp.)
- Small R^{-1} : large M_H required



Warped Extra Dimensions (Randall-Sundrum)

RS model characterized by one warped ED, confined by two three-branes

- One brane contains SM particles
- Extension: SM particles also in bulk

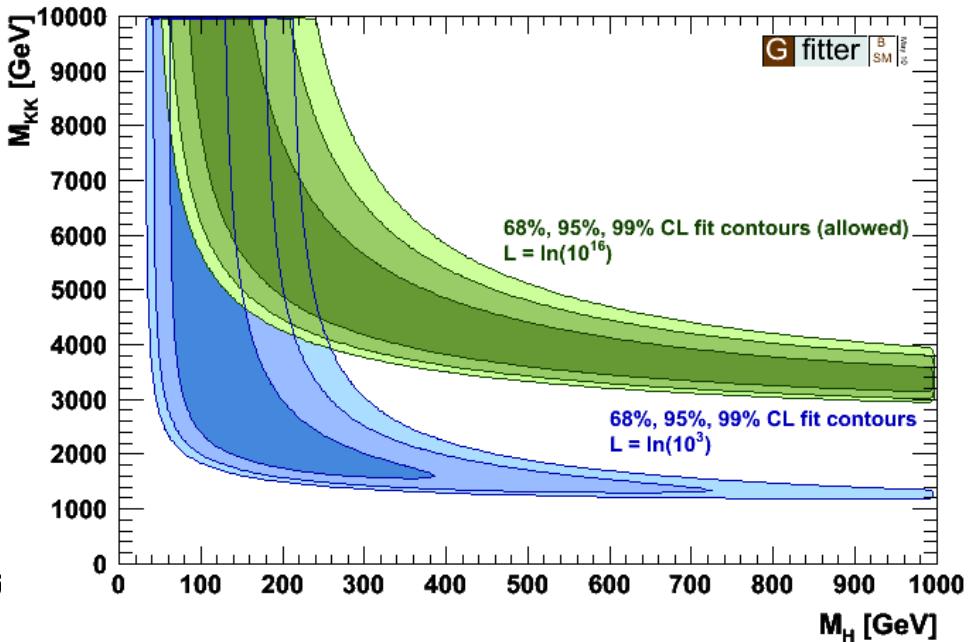
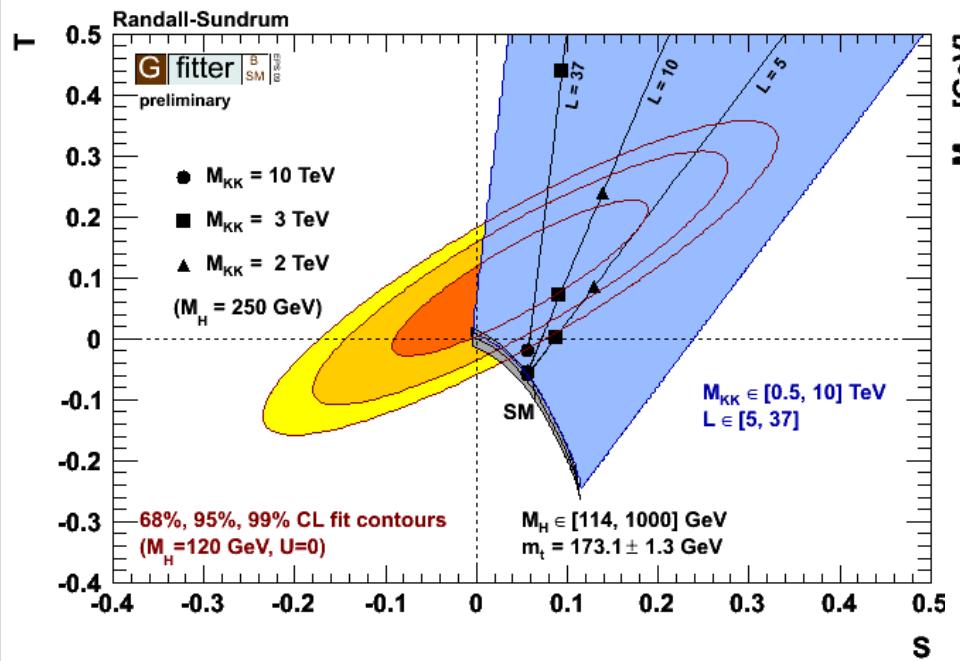
SM particles accompanied by towers of heavy KK modes.

Model parameters

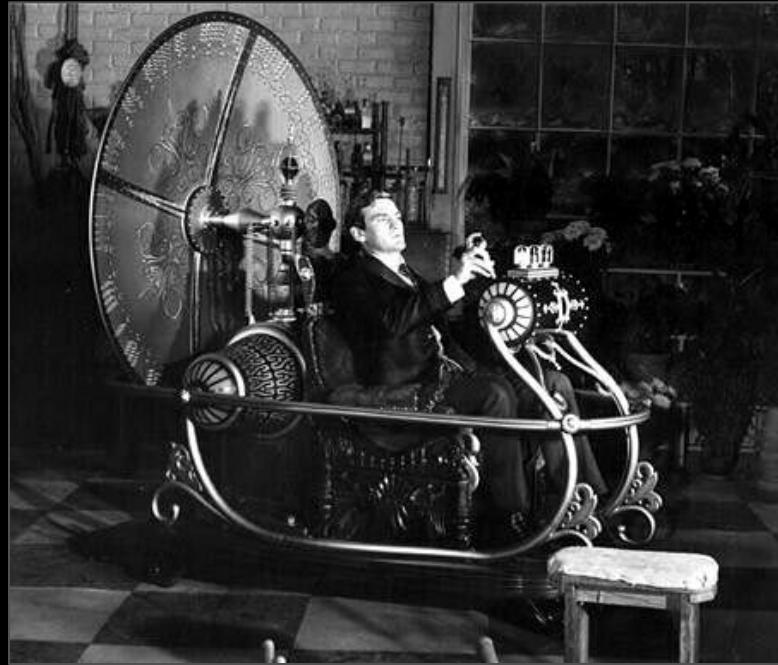
- L : inverse warp factor
- M_{KK} : KK mass scale

Results:

- Large values of T (linear in L)
- Large L requires large M_{KK} (and small M_H)



The Future of the Electroweak Fit ... (?)



Prospects for LHC, ILC and ILC with Giga-Z

New colliders (LHC/ILC) will increase precision in electroweak observables

- Improvement of the predictive power of the fit
- Higgs discovery → testing goodness-of-fit → sensitivity to new physics

Expected improvement from LHC (10 fb^{-1}):

- δM_W : 25 MeV → 15 MeV (at least)
[did not include A_{FB} from $Z \rightarrow ll$ in this study]
- δm_t : 1.2 GeV → 1.0 GeV

Expected improvement from ILC:

- From threshold scan $\delta m_t = 50 \text{ MeV}$, translates to 100–200 MeV on the running mass

Expected improvement from GigaZ:

- From WW threshold scan: $\delta M_W = 6 \text{ MeV}$
- From A_{LR} : $\delta \sin^2 \theta'_{\text{eff}}$: $17 \cdot 10^{-5} \rightarrow 1.3 \cdot 10^{-5}$
- δR_I^0 : $2.5 \cdot 10^{-2} \rightarrow 0.4 \cdot 10^{-2}$

Improved determination of $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$ will help

- Needs improvement in hadronic cross section data around cc resonance, and on QCD prediction of inclusive cross section
- Expected uncertainty of $7 \cdot 10^{-5}$ (today $10 \cdot 10^{-5}$) if relative cross-section precision below J/Ψ at 1% [Jegerlehner, hep-ph/0105283]
- Experiments with better acceptances and control of systematics needed
- Promising: ISR analyses at B and Φ factories; new data from BES-III

Prospects for LHC, ILC and ILC with Giga-Z

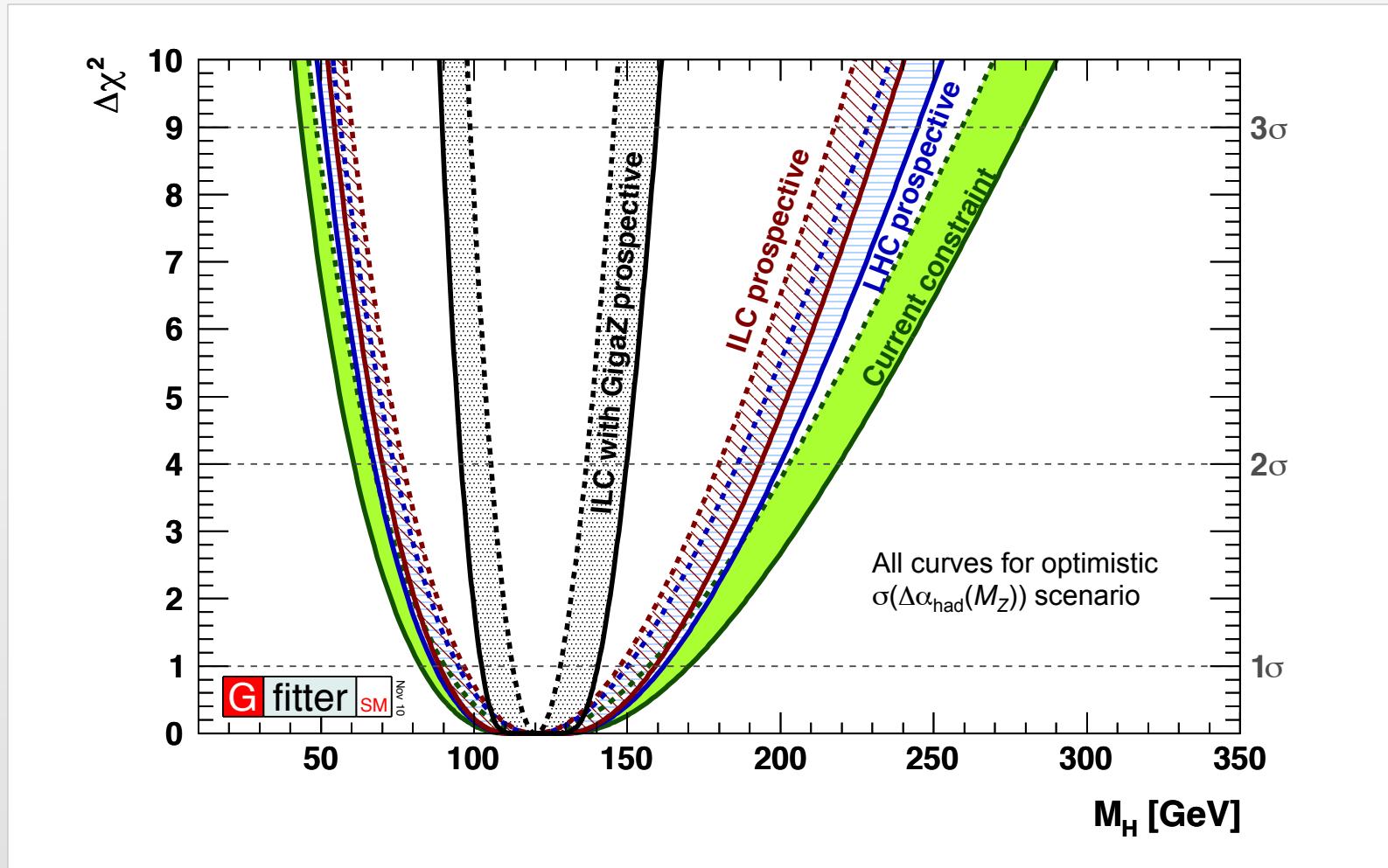
Fit inputs and results under various conditions

Quantity	Expected uncertainty			
	Present	LHC	ILC	GigaZ (ILC)
M_W [MeV]	23	15	15	6
m_t [GeV]	1.1	1.0	0.2	0.1
$\sin^2\theta_{\text{eff}}^\ell$ [10^{-5}]	17	17	17	1.3
R_ℓ^0 [10^{-2}]	2.5	2.5	2.5	0.4
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ [10^{-5}]	10 (7)	10 (7)	10 (7)	10 (7)
$M_H (= 120 \text{ GeV})$ [GeV]	$^{+53}_{-40} \left(^{+50}_{-37} \right) \left[^{+37}_{-30} \right]$	$^{+44}_{-35} \left(^{+42}_{-33} \right) \left[^{+30}_{-25} \right]$	$^{+42}_{-33} \left(^{+39}_{-31} \right) \left[^{+27}_{-24} \right]$	$^{+26}_{-23} \left(^{+20}_{-18} \right) \left[^{+8}_{-8} \right]$
$\alpha_s(M_Z^2)$ [10^{-4}]	28	28	28	7

Input from: [ATLAS, Physics TDR (1999)] [CMS, Physics TDR (2006)] [A. Djouadi et al., arXiv:0709.1893][I. Borjanovic, EPJ C39S2, 63 (2005)] [S. Haywood et al., hep-ph/0003275] [R. Hawkings, K. Mönig, EPJ direct C1, 8 (1999)] [A. H. Hoang et al., EPJ direct C2, 1 (2000)] [M. Winter, LC-PHSM-2001-016]

Prospects for LHC, ILC and ILC with Giga-Z

Results on M_H , including (solid) and excluding (dotted) theoretical errors



Prospects for LHC, ILC and ILC with Giga-Z

Results on M_H , including (solid) and excluding (dotted) theoretical errors

On Witek's point in the introduction:

“Can we indirectly exclude the SM Higgs before it is not discovered?”

Look at: $\Delta\chi^2 = \chi^2(M_H = 114.5 \text{ GeV}) - \chi^2(M_H \text{ free})$ **Caution: this is a biased test !**



Prospects for LHC, ILC and ILC with Giga-Z

Results on M_H from LEP II (dashed) and ILC (solid) at 10% global errors

That was it – conclusions:

New precision electroweak data continue to come in !

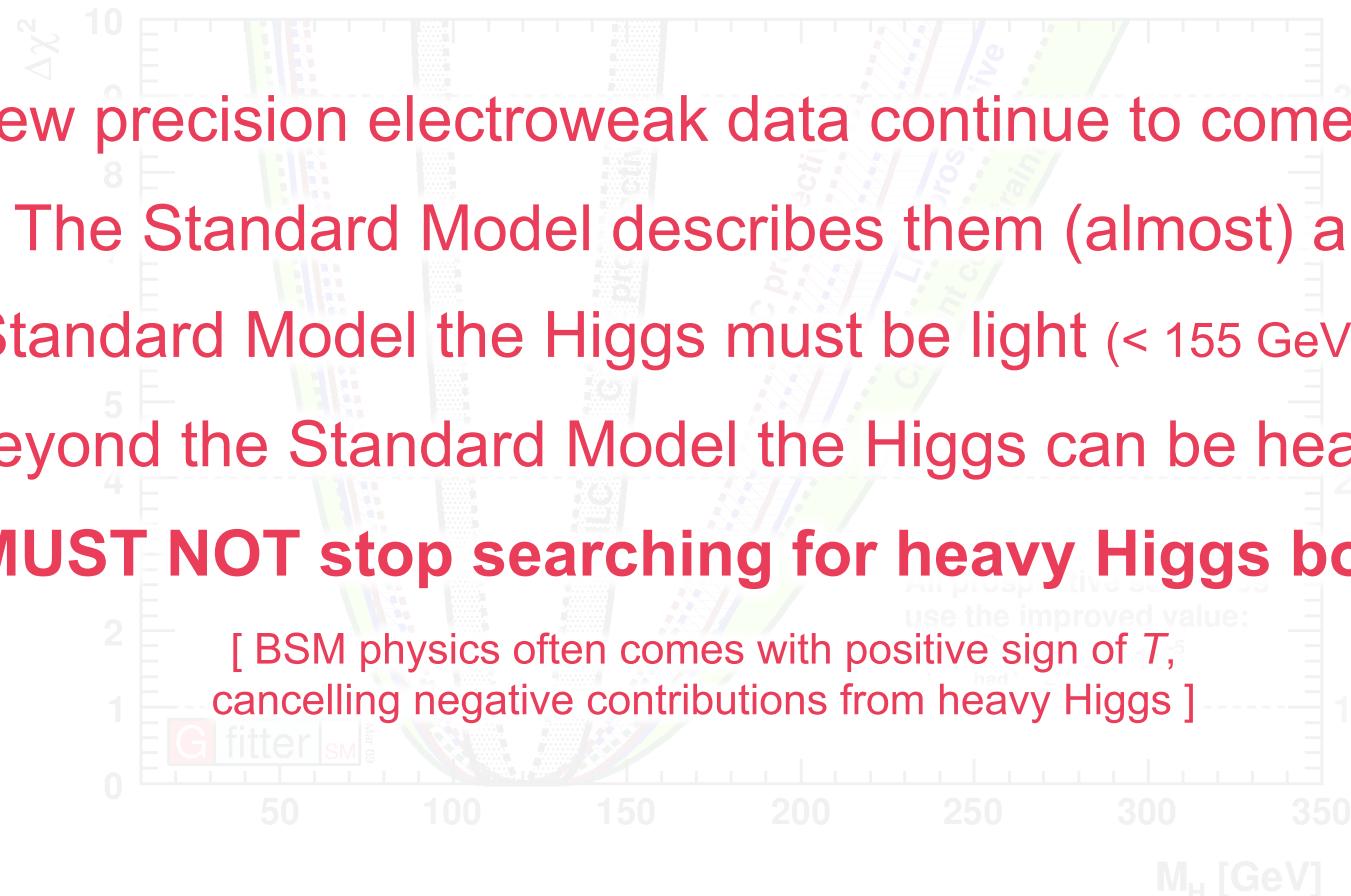
The Standard Model describes them (almost) all.

In the Standard Model the Higgs must be light (< 155 GeV at 95% CL).

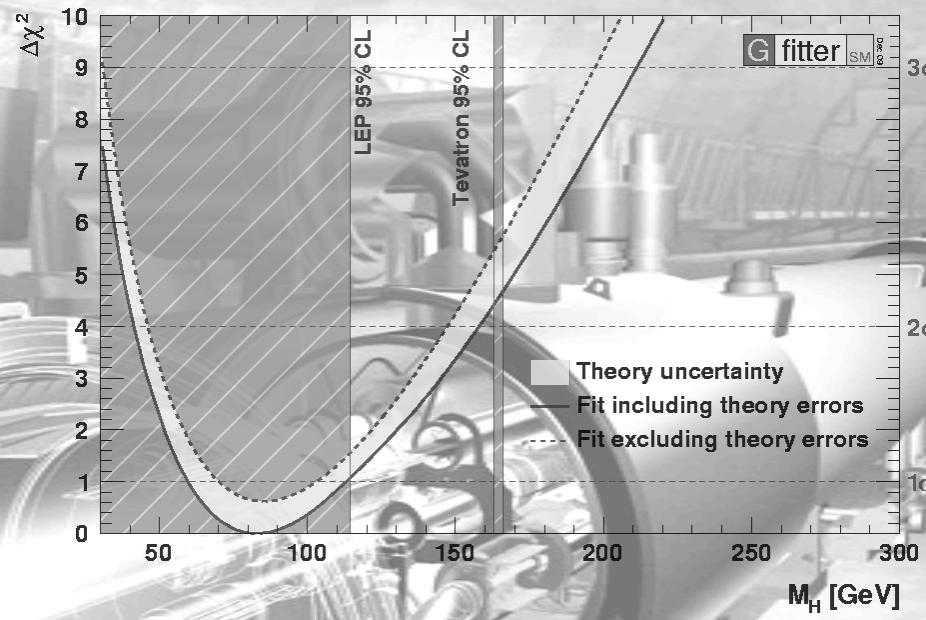
Beyond the Standard Model the Higgs can be heavy !

→ **MUST NOT stop searching for heavy Higgs boson !**

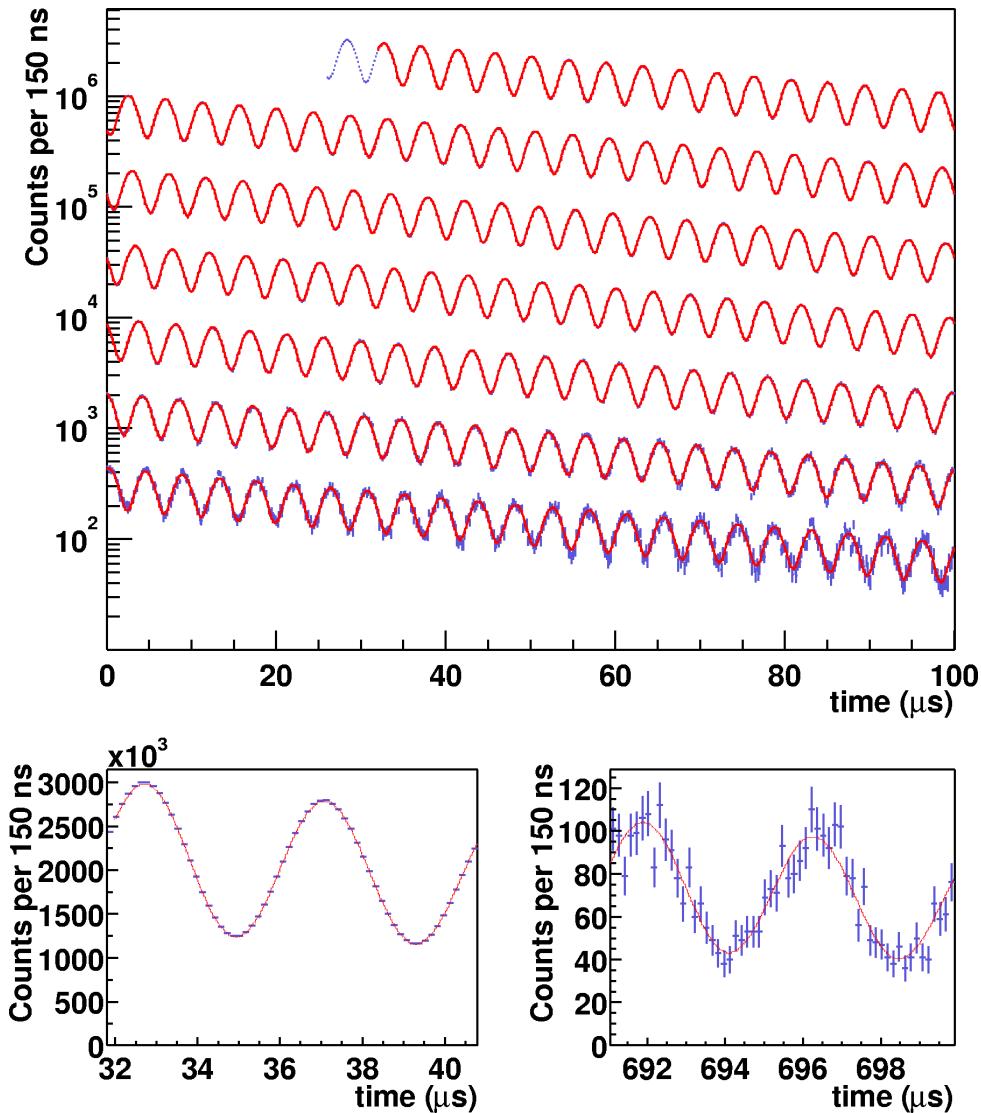
[BSM physics often comes with positive sign of T_5 ,
canceling negative contributions from heavy Higgs]



Additional slides



Digression: anomalous magnetic moment of the muon



Measurement using polarised muons in cyclotron with homogeneous B field. Direction of decay electrons/positrons correlated with muons precessing muon spin.

Observe positron rate in scintillators mounted along ring (see *left plot*)

Difference between spin precession and cyclotron frequency:

$$\vec{\omega}_a = \frac{e}{m_\mu c} \vec{a}_\mu \vec{B}$$

obtained from fit to:

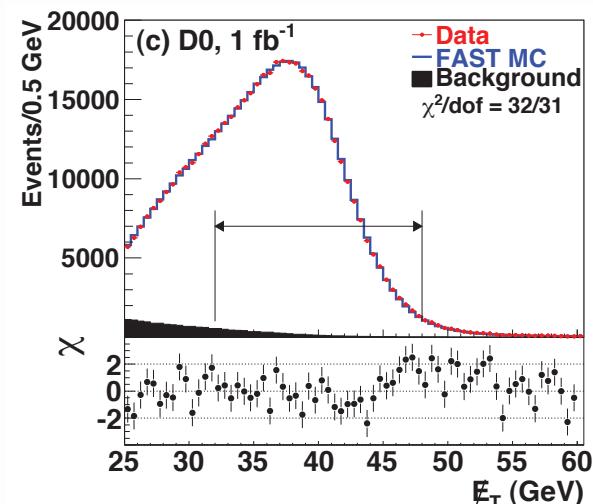
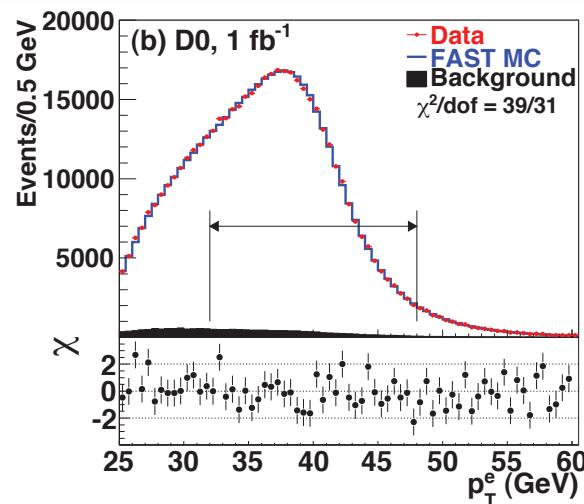
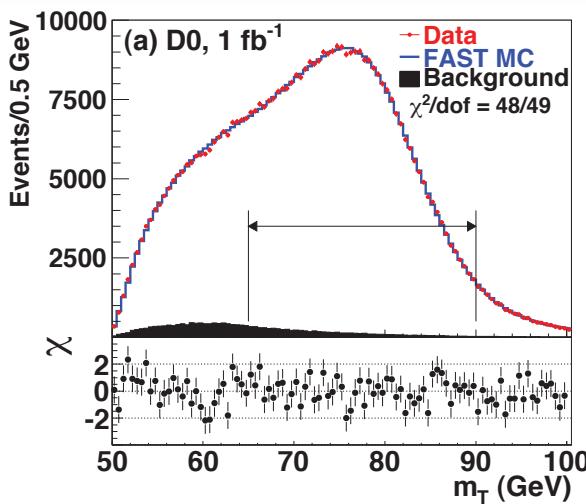
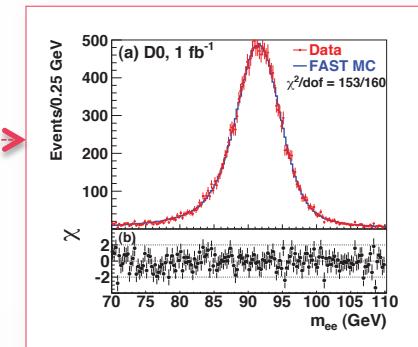
$$N(t) = N_0 e^{-t/\gamma\tau} [1 + A \sin(\omega_a t + \phi)]$$

Plot taken from:
E821 ($g-2$), hep-ex/0202024

Precision Measurement of the W mass

Recent D0 measurement of M_W in $W \rightarrow e\nu$

- Analysis relies on energy calibration with $Z \rightarrow ee$
- Result: $M_W = (80.401 \pm 0.021 \pm 0.038) \text{ GeV}$
- Greatly deserves the label “precision measurement”



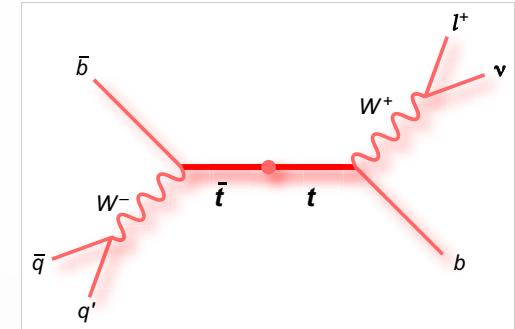
The (a) m_T , (b) p_T^e , and (c) $E_{T,\text{miss}}$ distributions for data and fastmc simulation with backgrounds. The χ values are shown below each distribution where $\chi_i = [N_i - (\text{fastmc}_i)]/\sigma_i$ for each point in the distribution, N_i is the data yield in bin i and only the statistical uncertainty is used. The fit ranges are indicated by the double-ended horizontal arrows.

Measurement of the top mass

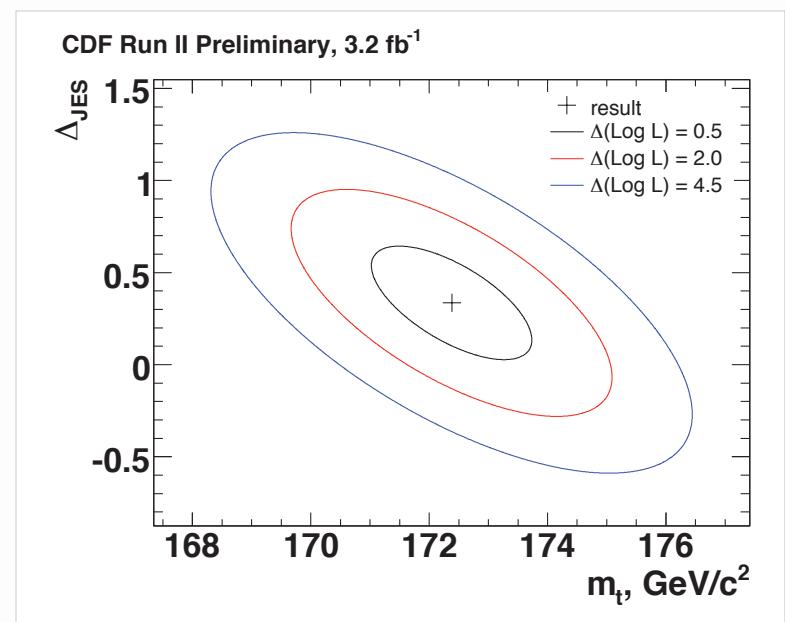
Top quark mass is measured in di-lepton (4%), lepton-jets (30%), and jets-jets (46%) modes

- Analysis relies strongly on identification of b -jets for background suppression and reduction of jet combinatorics
- Use multivariate methods to suppress backgrounds
- “In situ” jet energy scale (JES) calibration in modes with jets

Fit method: parameterise templates depending on top mass and JES for sensitive variables (e.g., $M_{\text{jet-jet}}$, $M_{\text{letp-jet}}$, ...), construct and maximise overall likelihood function



The lepton-jets channel provides most precise m_t measurement



Measurement of the top mass

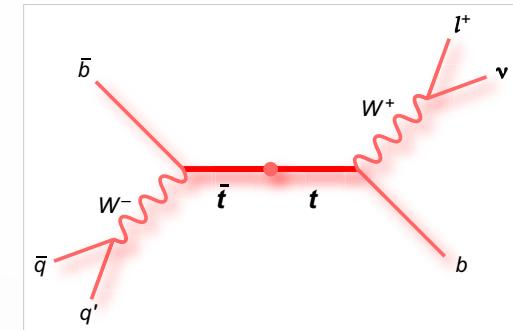
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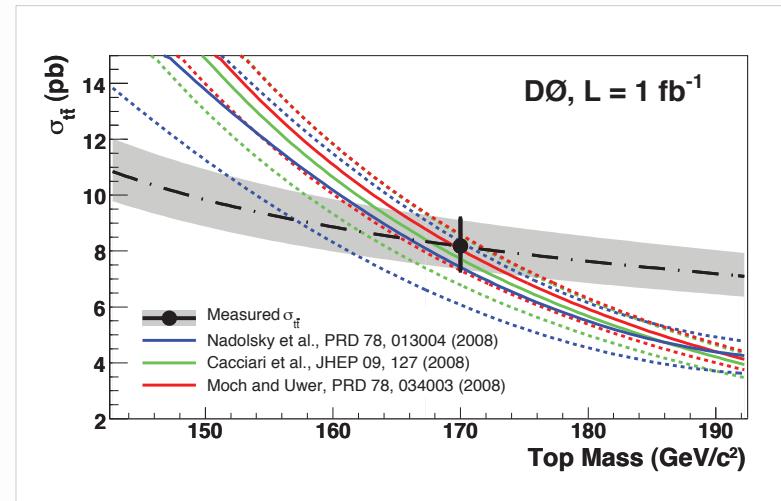
Fit method: parameterise templates depending on top mass and JES for sensitive variables (e.g., $M_{\text{jet-jet}}$, $M_{\text{letp-jet}}$, ...), construct and maximise overall likelihood function

Can also extract m_t from top cross section measurement

- Complementary method [PRD 80, 071102 (2009)]
- **Unambiguous** definition of running top mass, but limited by precision on luminosity



The lepton-jets channel provides most precise m_t measurement



Oblique Parameters and Corrections

Definitions of S, T, U, V, W, X :

[STU parameters suffice when $(q/M)^2$ small, so that linear approximation is accurate]

[Burgess et al., PLB 326, 276
(1994), PRD 49, 6115 (1994)]

$$\frac{\alpha S}{4s_w^2 c_w^2} = \left[\frac{\delta\Pi_{zz}(M_z^2) - \delta\Pi_{zz}(0)}{M_z^2} \right] - \frac{(c_w^2 - s_w^2)}{s_w c_w} \delta\Pi'_{z\gamma}(0) - \delta\Pi'_{\gamma\gamma}(0) ,$$

$$\alpha T = \frac{\delta\Pi_{ww}(0)}{M_w^2} - \frac{\delta\Pi_{zz}(0)}{M_z^2} ,$$

$$\begin{aligned} \frac{\alpha U}{4s_w^2} &= \left[\frac{\delta\Pi_{ww}(M_w^2) - \delta\Pi_{ww}(0)}{M_w^2} \right] - c_w^2 \left[\frac{\delta\Pi_{zz}(M_z^2) - \delta\Pi_{zz}(0)}{M_z^2} \right] \\ &\quad - s_w^2 \delta\Pi'_{\gamma\gamma}(0) - 2s_w c_w \delta\Pi'_{z\gamma}(0) , \end{aligned}$$

$$\alpha V = \delta\Pi'_{zz}(M_z^2) - \left[\frac{\delta\Pi_{zz}(M_z^2) - \delta\Pi_{zz}(0)}{M_z^2} \right] ,$$

$$\alpha W = \delta\Pi'_{ww}(M_w^2) - \left[\frac{\delta\Pi_{ww}(M_w^2) - \delta\Pi_{ww}(0)}{M_w^2} \right] ,$$

$$\alpha X = -s_w c_w \left[\frac{\delta\Pi_{z\gamma}(M_z^2)}{M_z^2} - \delta\Pi'_{z\gamma}(0) \right] .$$

Oblique Parameters and Corrections

Dependence of electroweak observables on S, T, U, V, W, X .

[The numerical values are based on $\alpha^{-1}(M_Z) = 128$ and $\sin^2\theta_W = 0.23$]

[Burgess et al., PLB 326, 276
(1994), PRD 49, 6115 (1994)]

$$\Gamma_z = (\Gamma_z)_{\text{SM}} - 0.00961S + 0.0263T + 0.0194V - 0.0207X \text{ [GeV]}$$

$$\Gamma_{bb} = (\Gamma_{bb})_{\text{SM}} - 0.00171S + 0.00416T + 0.00295V - 0.00369X \text{ [GeV]}$$

$$\Gamma_{\ell^+\ell^-} = (\Gamma_{\ell^+\ell^-})_{\text{SM}} - 0.000192S + 0.000790T + 0.000653V - 0.000416X \text{ [GeV]}$$

$$\Gamma_{\text{had}} = (\Gamma_{\text{had}})_{\text{SM}} - 0.00901S + 0.0200T + 0.0136V - 0.0195X \text{ [GeV]}$$

$$A_{\text{FB}(\mu)} = (A_{\text{FB}(\mu)})_{\text{SM}} - 0.00677S + 0.00479T - 0.0146X$$

$$A_{\text{pol}(\tau)} = (A_{\text{pol}(\tau)})_{\text{SM}} - 0.0284S + 0.0201T - 0.0613X$$

$$A_{e(P\tau)} = (A_{e(P\tau)})_{\text{SM}} - 0.0284S + 0.0201T - 0.0613X$$

$$A_{\text{FB}(b)} = (A_{\text{FB}(b)})_{\text{SM}} - 0.0188S + 0.0131T - 0.0406X$$

$$A_{\text{FB}(c)} = (A_{\text{FB}(c)})_{\text{SM}} - 0.0147S + 0.0104T - 0.03175X$$

$$A_{\text{LR}} = (A_{\text{LR}})_{\text{SM}} - 0.0284S + 0.0201T - 0.0613X$$

$$M_W^2 = (M_W^2)_{\text{SM}} (1 - 0.00723S + 0.0111T + 0.00849U)$$

$$\Gamma_w = (\Gamma_w)_{\text{SM}} (1 - 0.00723S - 0.00333T + 0.00849U + 0.00781W)$$

$$g_L^2 = (g_L^2)_{\text{SM}} - 0.00269S + 0.00663T$$

$$g_R^2 = (g_R^2)_{\text{SM}} + 0.000937S - 0.000192T$$

$$g_{V,(\nu e \rightarrow \nu e)}^e = (g_V^e)_{\text{SM}} + 0.00723S - 0.00541T$$

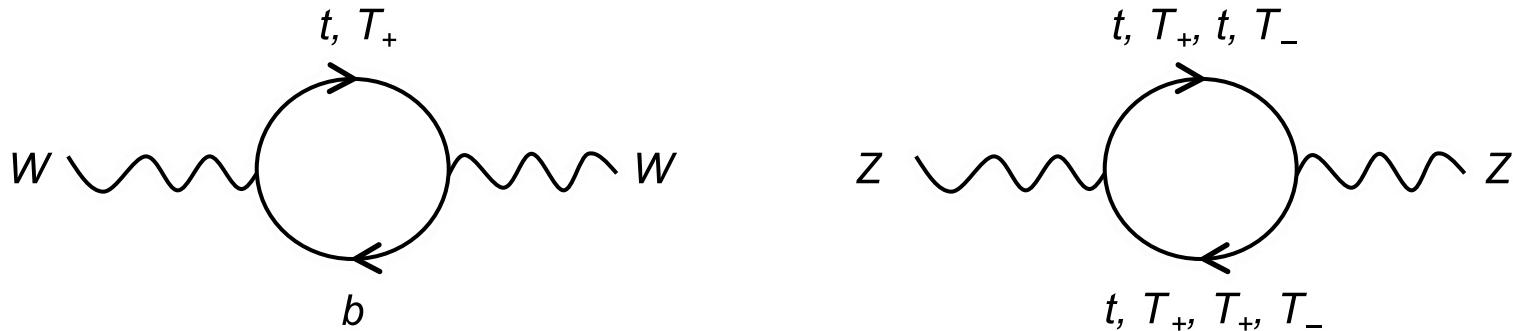
$$g_{A,(\nu e \rightarrow \nu e)}^e = (g_A^e)_{\text{SM}} - 0.00395T$$

$$Q_W(^{133}_{55}\text{Cs}) = Q_W(\text{Cs})_{\text{SM}} - 0.795S - 0.0116T$$

Little Higgs Models (LHM)

- LHM: solves hierarchy problem, possible explanation for EWSM
 - SM contributions to Higgs mass cancelled by new particles
- Non-linear sigma model, broken Global SU(5) / SO(5) symmetry
 - Higgs = lightest pseudo Nambu-Goldstone boson
 - New SM-like fermions and gauge bosons at TeV scale
- T -parity = symmetry similar to SUSY R -parity (note: not *time-invariance* !)
 - Forbids tree-level couplings of new gauge bosons (T -odd) to SM particles (T -even)
 - LHM provides natural dark matter candidate
- Two new top states: T -even T_+ and T -odd T_-

One-loop oblique corrections from LH top sector with T -parity:



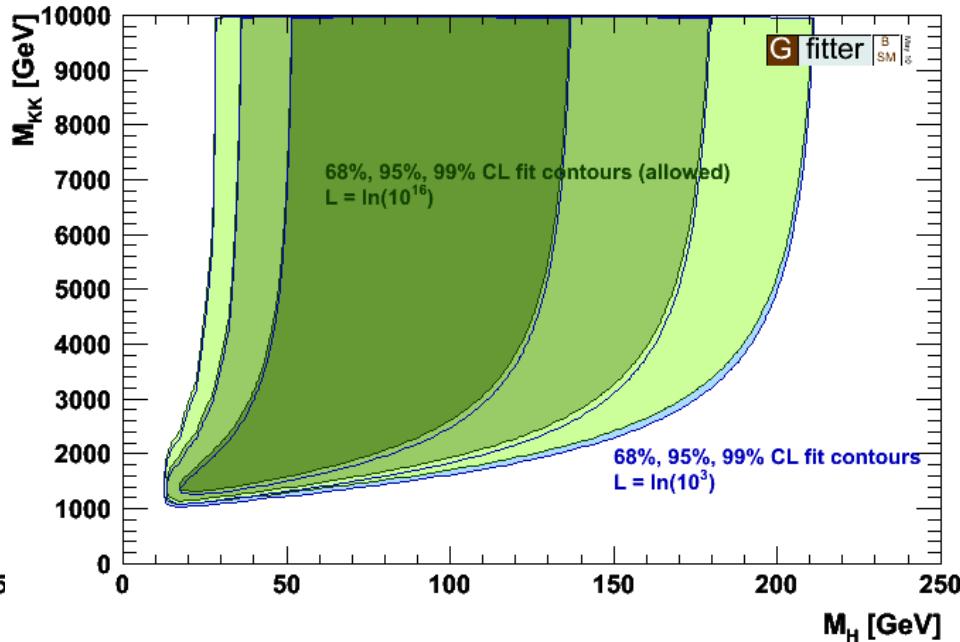
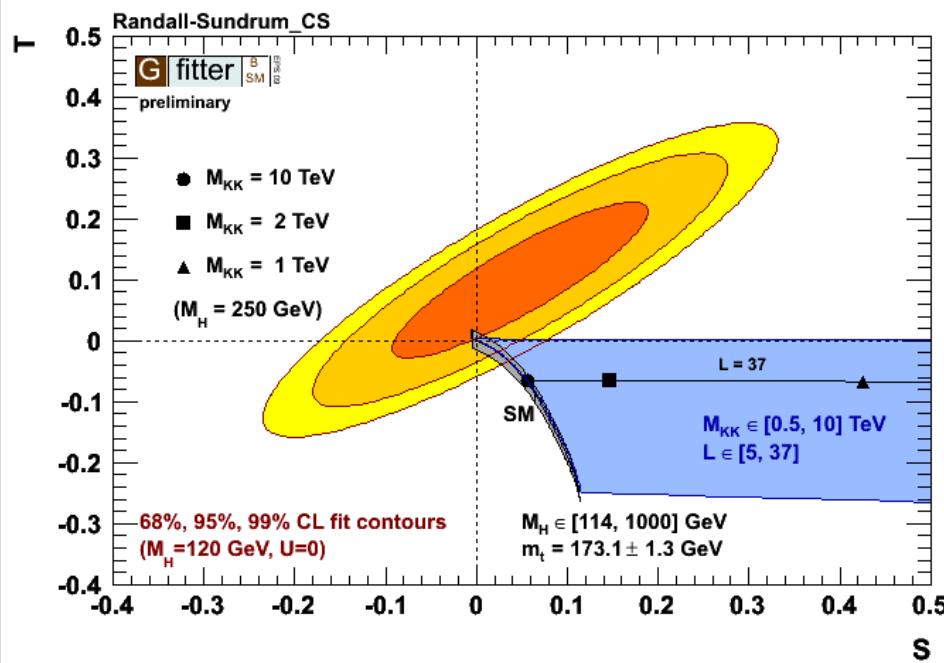
Warped Extra Dimensions w/ Custodial Symmetry

Goal: avoid large T values

→ Introduce so-called **custodial isospin gauge symmetry** in the bulk

- Extend hypercharge group to $SU(2)_R \times U(1)_X$
- Bulk group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$
- Broken to $SU(3)_C \times SU(2)_L \times U(1)_Y$ on UV brane
- IR brane $SU(2)_R$ symmetric
- Right-handed fermionic fields are doublets

Results: only small M_H allowed



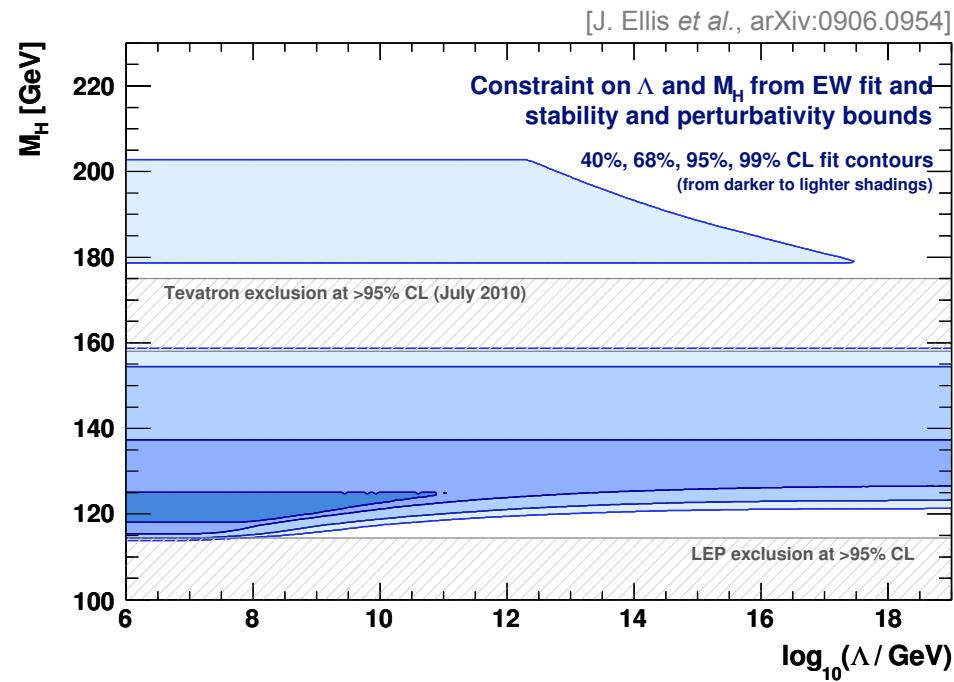
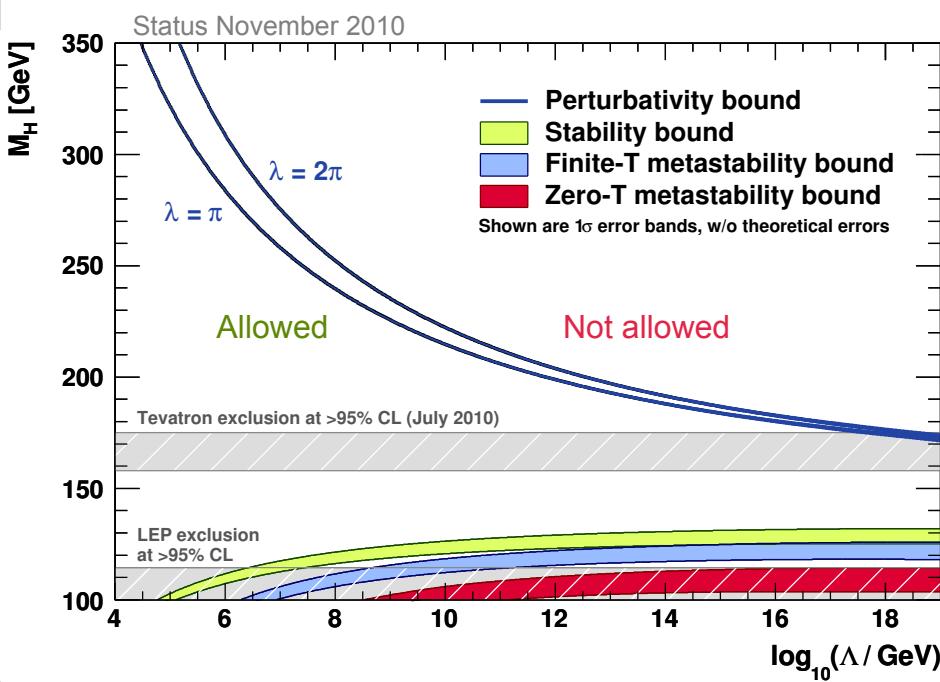
The Fate of the Standard Model



Driving the SM to M_{Planck}

The behaviour of the quartic Higgs couplings as function of the cut-off scale Λ puts bounds on M_H

- For too large M_H , the couplings become **non-perturbative** (“triviality” or “blow-up” scenario)
- For too small M_H , the vacuum becomes **unstable**
→ obtain three lower bounds on M_H from different requirement: **absolute stability, finite- T and zero- T metastability**



Driving the SM to M_{Planck}

- Requiring that the SM cannot develop a minimum deeper than the electroweak vacuum up to the Planck scale (i.e., $\lambda(\mu) > 0$, for all $\mu < \Lambda$) gives the **stability bound** :

$$M_H > 128.6 \text{ GeV} + 2.6 \text{ GeV} \cdot \left(\frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 2.2 \text{ GeV} \cdot \left(\frac{\alpha_s(M_Z) - 0.1193}{0.0028} \right) \pm 1 \text{ GeV}$$

- Requiring that the local EW vacuum survives for a time longer than the age of the universe, before quantum tunneling into the deeper vacuum, gives **zero-T metastability bound** :

$$M_H > 108.9 \text{ GeV} + 4.0 \text{ GeV} \cdot \left(\frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 3.5 \text{ GeV} \cdot \left(\frac{\alpha_s(M_Z) - 0.1193}{0.0028} \right) \pm 3 \text{ GeV}$$

- Requiring the local SM minimum to be stable against thermal fluctuations up to temperatures as large as the Planck scale translates into **finite-T metastability bound** :

$$M_H > 122.0 \text{ GeV} + 3.0 \text{ GeV} \cdot \left(\frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 2.3 \text{ GeV} \cdot \left(\frac{\alpha_s(M_Z) - 0.1193}{0.0028} \right) \pm 3 \text{ GeV}$$

Driving the SM to M_{Planck}

Assuming the SM to be valid up to Planck scale, we can derive likelihoods for the different scenarios

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