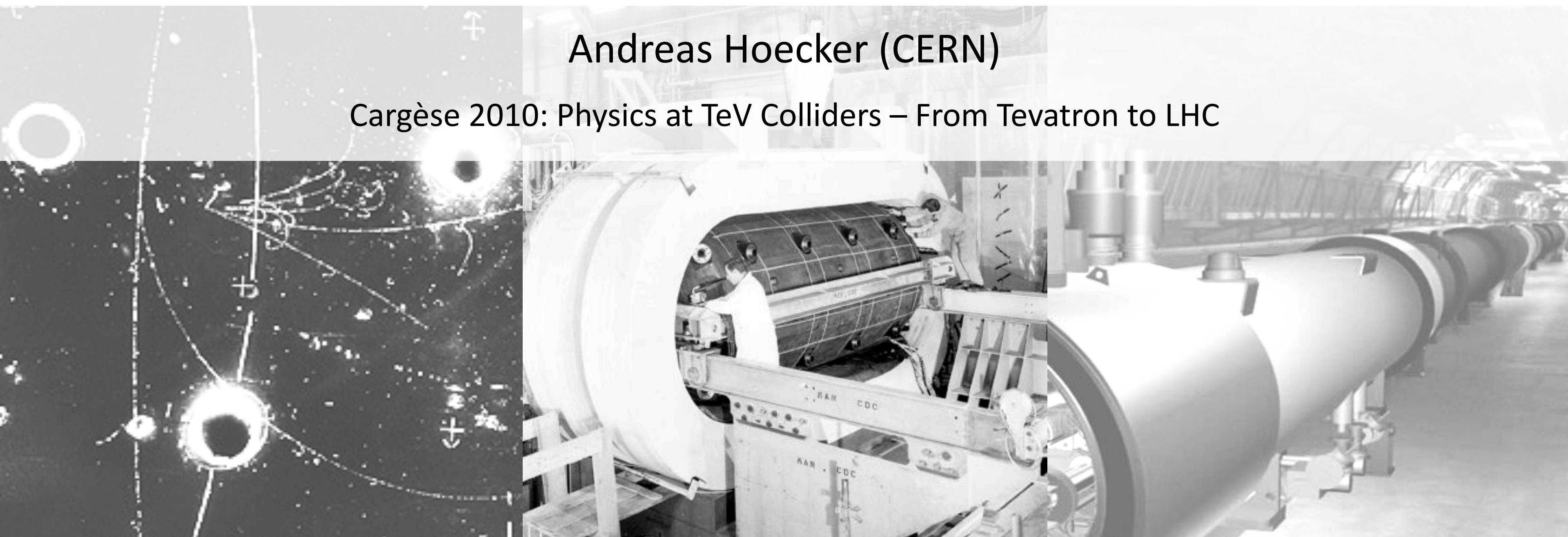
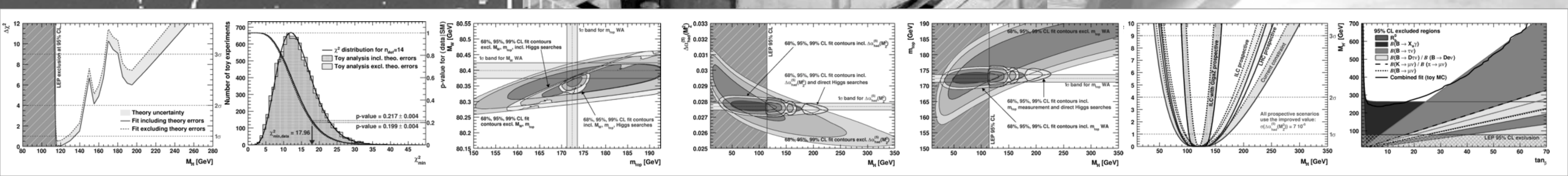
Introduction to Higgs and Electroweak Precision Physics (III)

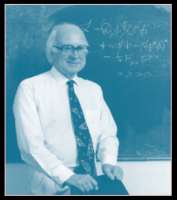


Andreas Hoecker (CERN)

Cargèse 2010: Physics at TeV Colliders – From Tevatron to LHC



Indirect Constraints on the Higgs



from Electroweak Precision Data

Precision measurements allow us to probe physics at much higher energy scales than the masses of the particles directly involved in experimental reactions by exploiting contributions from quantum loops. These tests do not only require accurate and well understood experimental data but also theoretical predictions with controlled uncertainties that match the experimental precision.

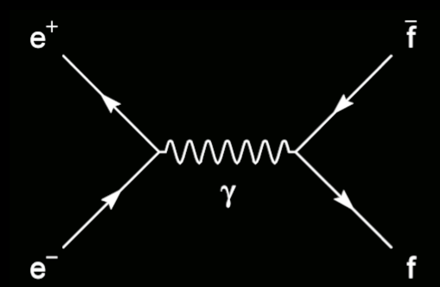
The global electroweak fit

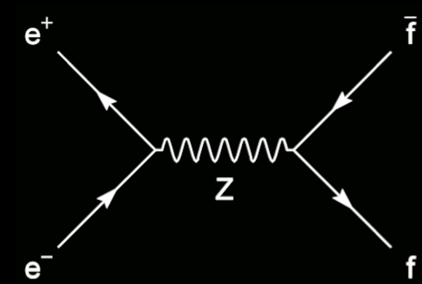
Since the Z^0 boson couples to all fermion-antifermion pairs, it is ideal for measuring and studying electroweak and strong interactions

The global electroweak fit

Most important experimental inputs to fit:

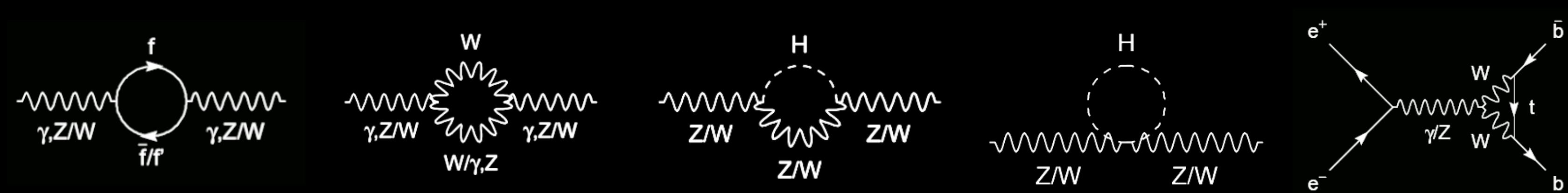
- Electroweak precision data measured at the Z^0 resonance
- Processes studied: $e^+e^- \rightarrow$ fermion + anti-fermion (quarks, charged leptons, neutrinos)
- Lowest order diagrams:





Z-to-fermion coupling has vector and axial-vector components → parity violation

- Photon exchange cross section falls with s^{-1}
- Resonance at $E_{CM} = M_Z$ (LEP-1, SLC), *W*-pair production at $E_{CM} > 2\ M_W$ (LEP-2)
- Electroweak unification: relation between weak and electromagnetic couplings
- Gauge sector of SM on tree level is given by 3 free parameters, *e.g.*, α, M_Z, G_F
- Sensitivity to heavy fermions (top) and bosons (Higgs) via **radiative corrections**:



And – remember – radiative corrections are important:

From electroweak unification: $M_W = M_Z \cdot \cos\theta_W$, or: $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$

- Use, *e.g.*, $\sin^2\theta_W = 0.2314 \pm 0.0002$ as obtained from deep-inelastic neutrino–nucleon scattering

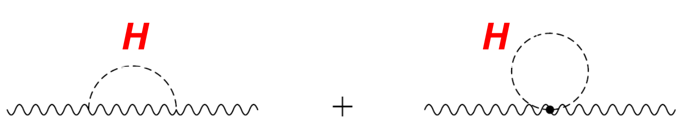
- …and using world average mass measurements from LEP and Tevatron gives:

$$M_W = (80.399 \pm 0.023)\ \text{GeV}|_{\text{LEP+Tevatron}} \stackrel{?}{=} (79.944 \pm 0.010)\ \text{GeV}|_{\text{EW theory (tree level)}}$$

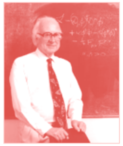
$$\sin^2\theta_W = 0.2314 \pm 0.0002 \stackrel{?}{=} 0.2226 \pm 0.0004|_{\text{EW theory (tree level)}}$$

Strong disagreement (20σ) !

Logarithmic Higgs dependence enters through virtual corrections, *e.g.* :



$$\Delta\rho_{(\text{Higgs})} = \frac{11 G_F m_Z^2 \cos^2\theta_W}{24\sqrt{2}\pi^2} \log\left(\frac{m_H^2}{m_W^2}\right)$$



Electroweak fits have a long history …

Based on a huge amount of preparatory work

- Needed to understand importance of loop corrections
- Precise Standard Model (SM) predictions and measurements required

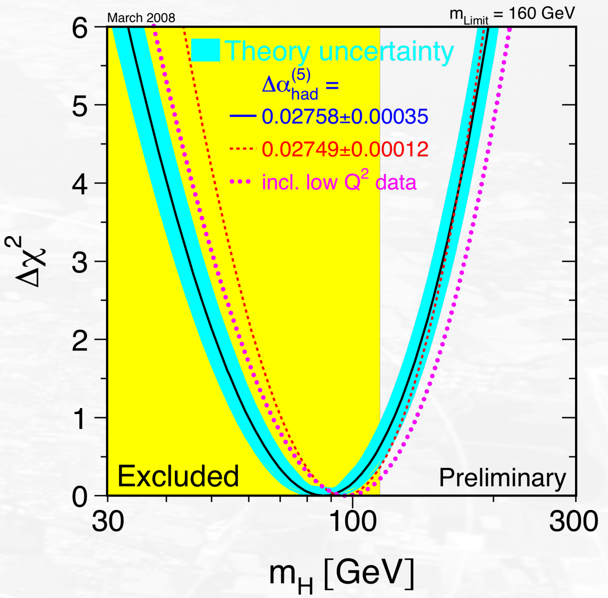
EW fits routinely performed by many groups

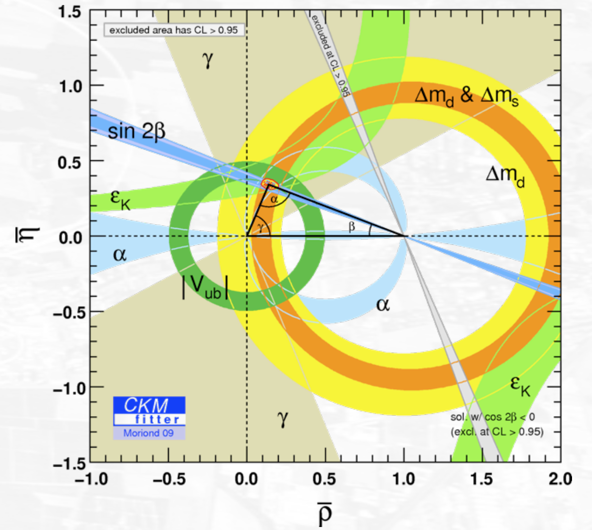
- D. Bardinet al. (ZFITTER), G. Passarinoet al. (TOPAZ0), LEP EW WG (M. Grünewald, K. Mönig *et al*.), J. Erler (GAPP), …
- Important results obtained !

Global SM fits also used at lower energies

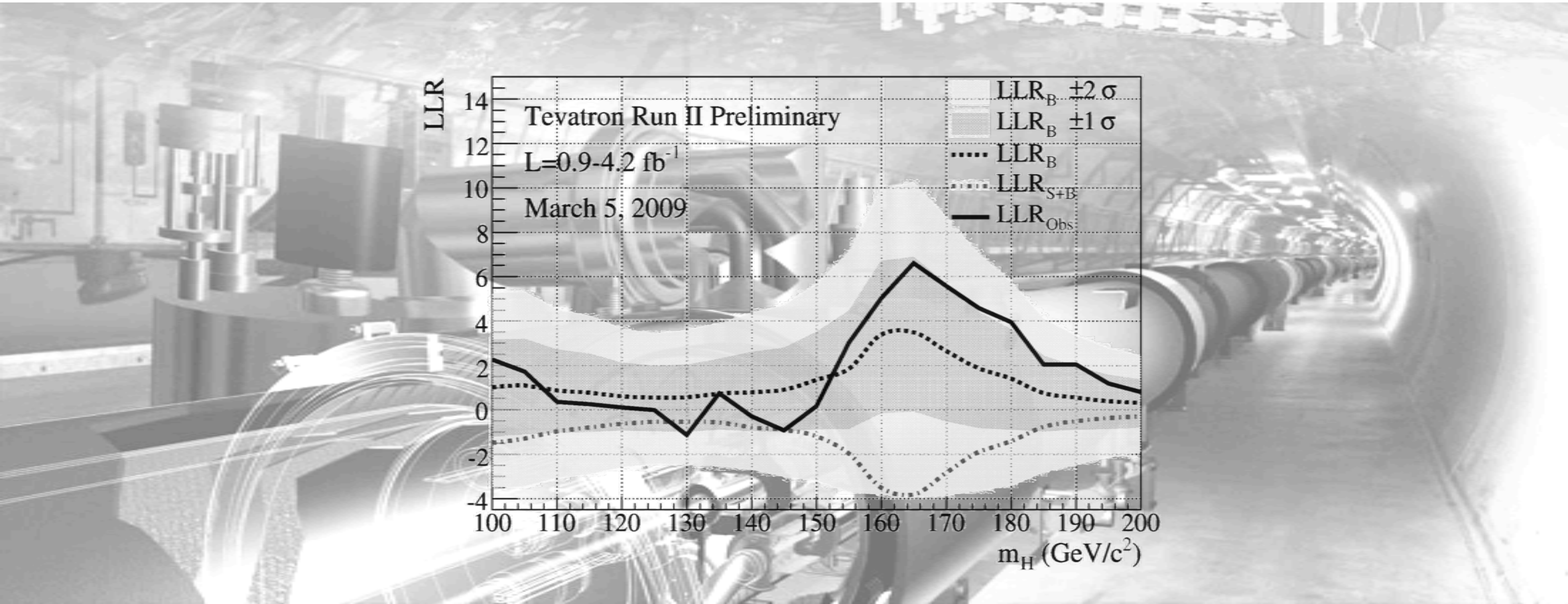
- CKMfitter (J. Charles *et al*.), UTfit (M. Bona *et al*.), …
- Mostly concentrating on CKM matrix

Also many groups pursuing global beyond-SM fits



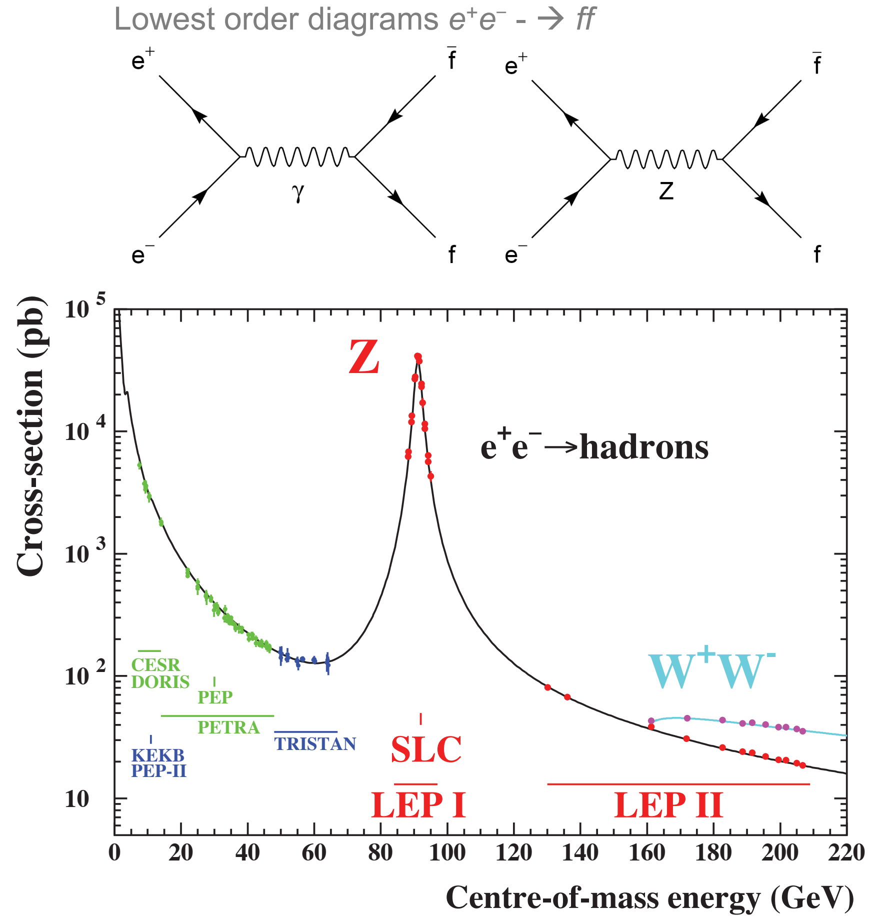


Experimental Inputs



Measurements at the Z Pole

Important experimental input to the fit: 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

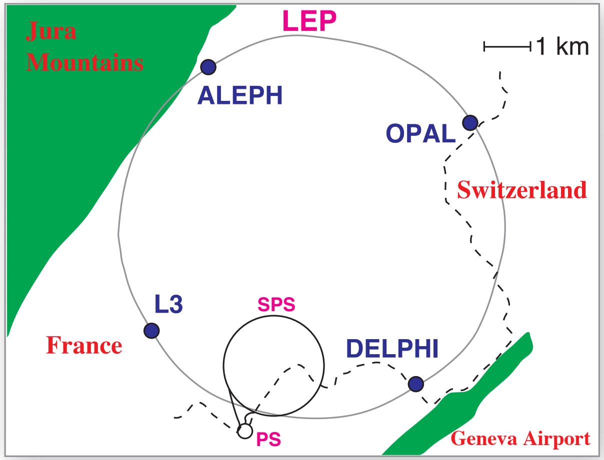
Hadronic cross-section:

- 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)

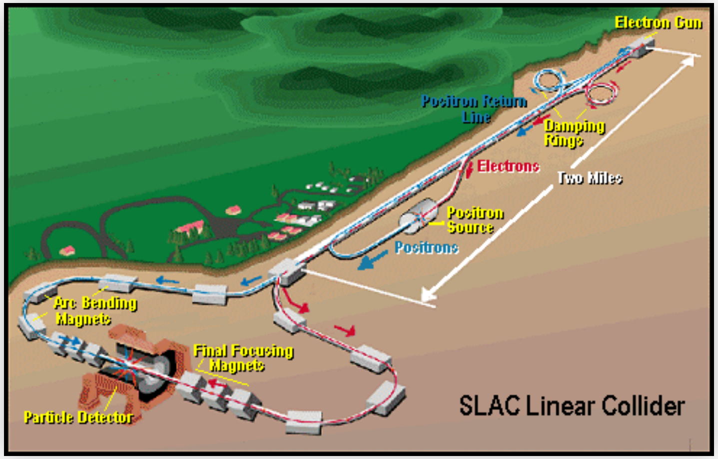
Measurements at the Z Pole

LEP I:



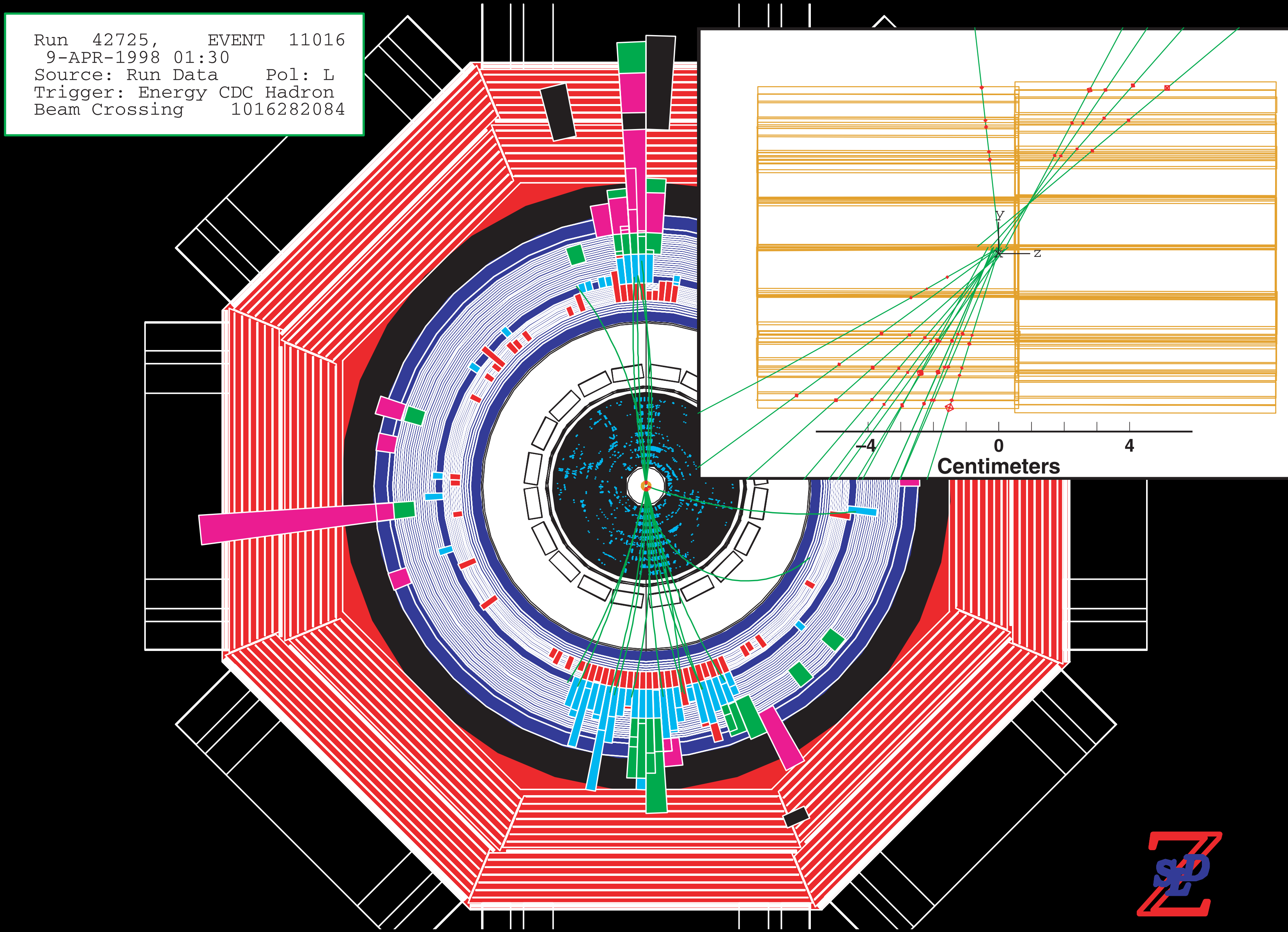
- Four experiments: ADLO
- 1989–1995: $\sqrt{s} \sim M_Z$
- $\sqrt{s}$ extremely well measured (2 MeV)
- Peak $L = 2 \cdot 10^{31}$ cm^{-2}s^{-1}
  - 1000 *Z*'s per hour per experiment
  - "Z-Factory"
- In total: ~17 million *Z* decays (SLD: 600k)

SLC:



- Low repetition rate (120 Hz cf. LEP: 45 kHz)
- Longitudinally polarized electron beam (up to $P_e \sim 80\%$)
- Small beam dimensions (1.5×0.7 μm^2, LEP: 150×5 μm^2) + low bunch rate allowed use of slow but high-res. CCD arrays

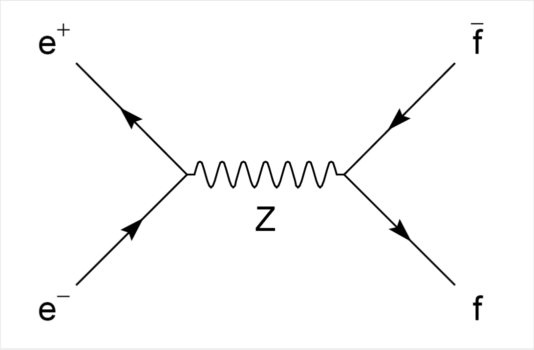
→ superior vertex reconstruction



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

Measurements at the Z Pole

A look at the theory – tree level relations



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

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

$$g_{A,f}^{(0)} \equiv g_{L,f}^{(0)} - g_{R,f}^{(0)} = I_3^f$$

Electroweak unification: relation between weak and electromagnetic couplings:

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

Since uncertainty on G_F and M_Z small, relation often used to eliminate direct M_W dependence:

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

Gauge sector of SM on tree level is given by 3 free parameters, *e.g.*: α, $\boldsymbol{M_Z}$, $\boldsymbol{G_F}$

Measurements 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:

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

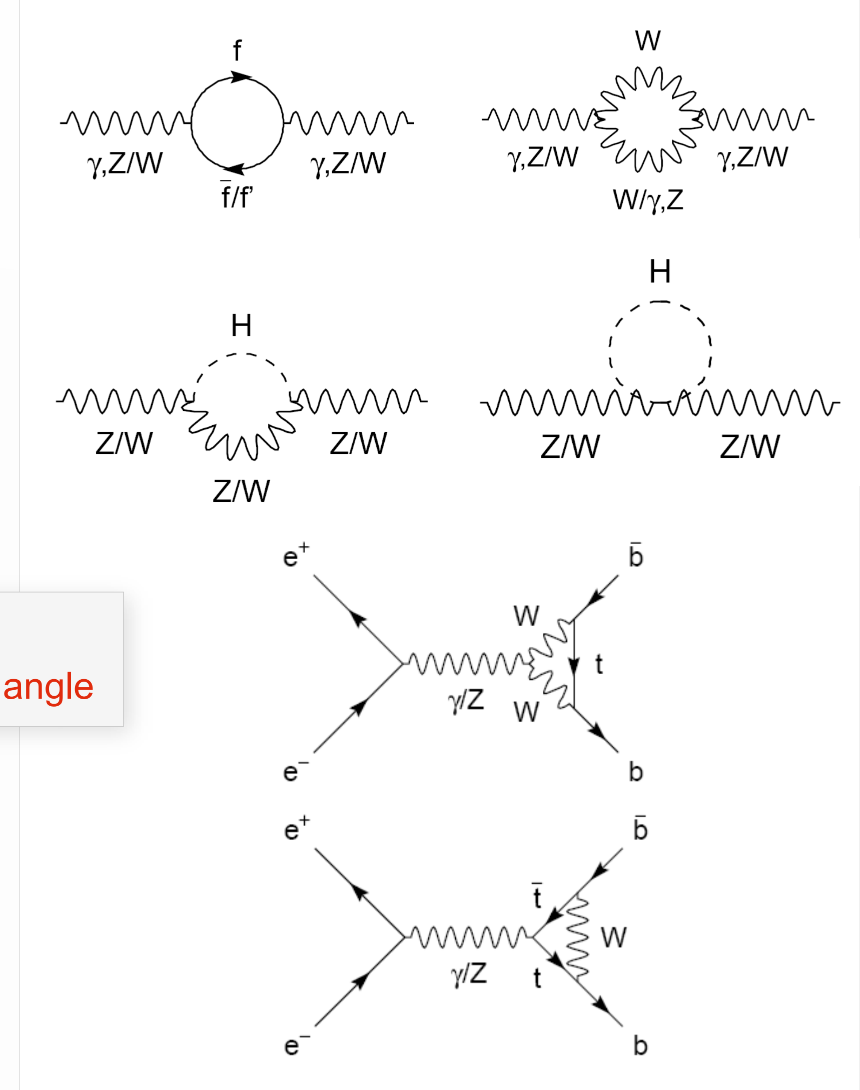
$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

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

ρ : overall scale
κ : on-shell mixing angle

- Modified W mass:

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



Measurements at the Z Pole

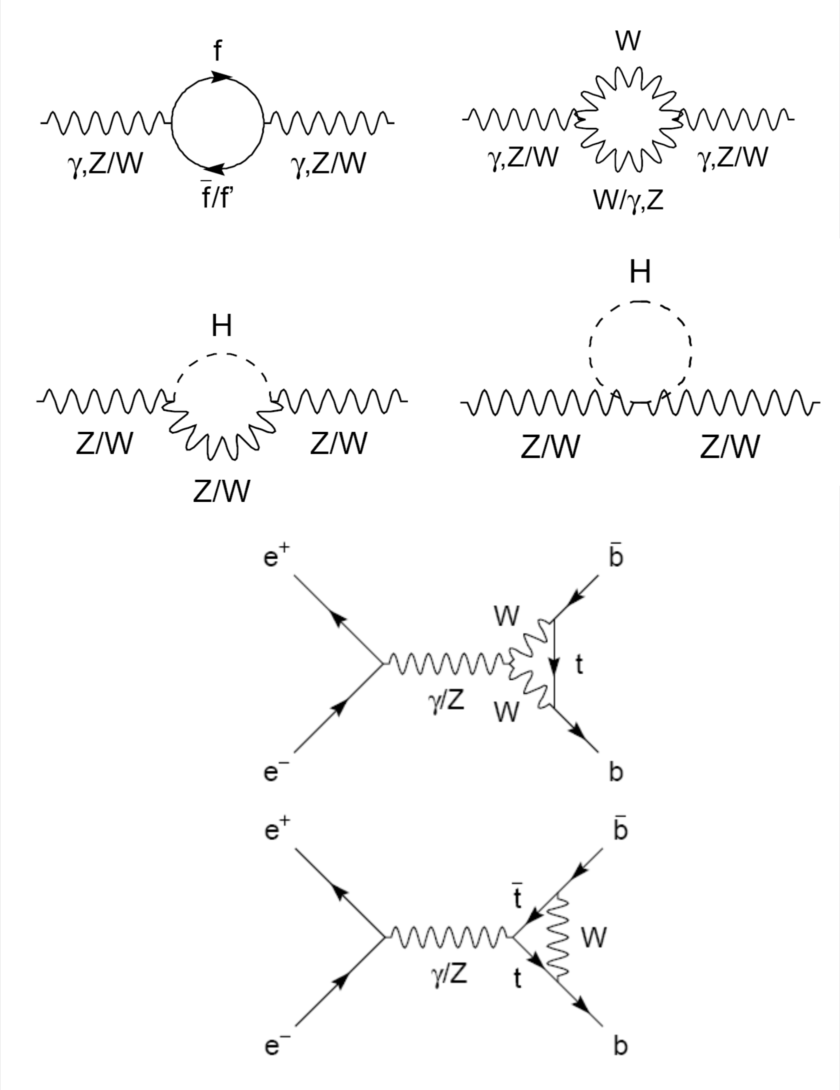
Radiative corrections –
modifying propagators and vertices

Important consequences

→ All other SM parameters enter the calculations

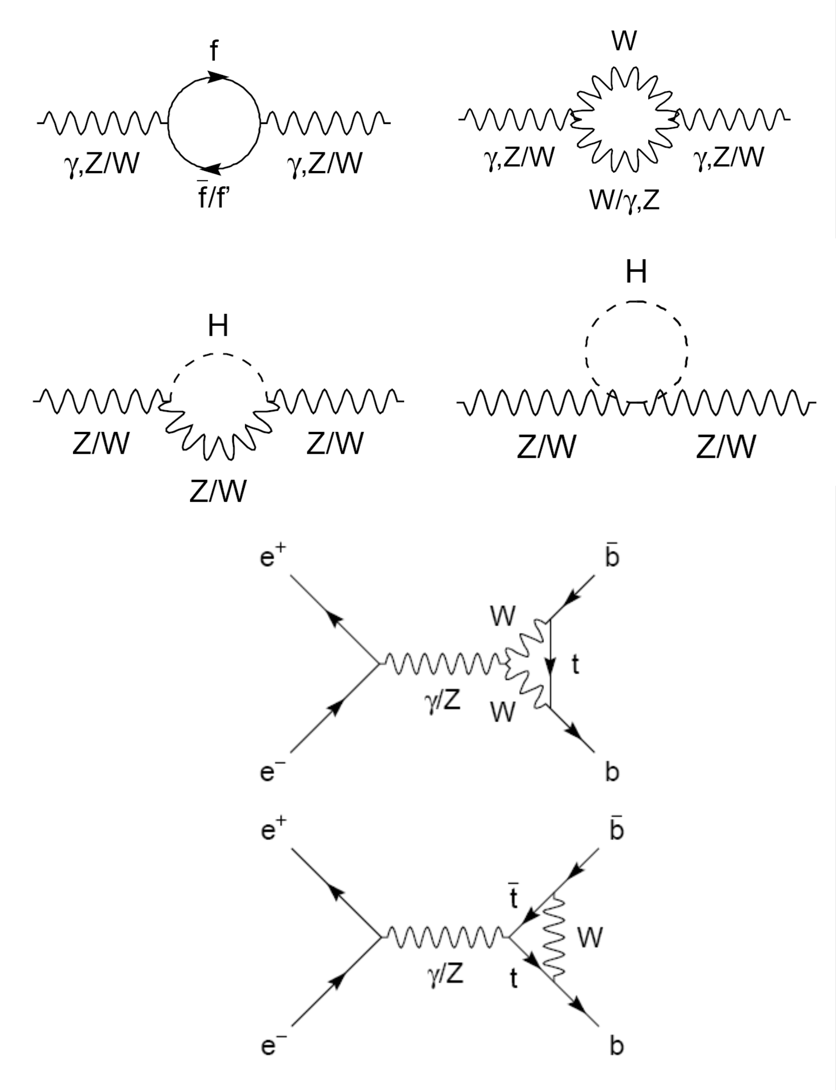
- In particular corrections are $\sim m^2_{top}$ and $\sim \ln(M_H)$
- Loop correction of the order ~1%.
- Precision observables measured at LEP/SLC to much better precision !

→ **Can test the SM and constraint the unknown SM Parameters**



Measurements 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:

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

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

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

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

Measurements at the Z Pole

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

$$\frac{2s}{\pi}\frac{1}{N_c^f}\frac{d\sigma_{ew}(e^+e^-\to f\bar{f})}{d\cos\theta} = \left|\alpha(s)\cdot Q_f\right|^2\left(1+\cos^2\theta\right)$$

$$-8\,\mathrm{Re}\left\{\alpha^*(s)Q_f\chi_{\mathrm{BW}}(s)\left[g_{V,e}g_{V,f}\left(1+\cos^2\theta\right)+2g_{A,e}g_{A,f}\cos\theta\right]\right\}$$

$$+16\left|\chi_{\mathrm{BW}}(s)\right|^2\left[\left(\left|g_{V,e}\right|^2+\left|g_{A,e}\right|^2\right)\left(\left|g_{V,f}\right|^2+\left|g_{A,f}\right|^2\right)\left(1+\cos^2\theta\right)+8\,\mathrm{Re}\left\{g_{V,e}g_{A,e}^*\right\}\mathrm{Re}\left\{g_{V,f}g_{A,f}^*\right\}\cos\theta\right]$$

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

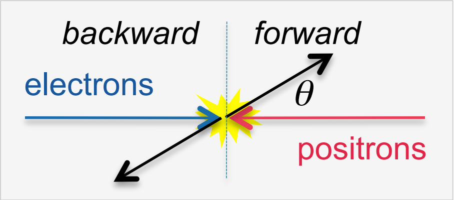
Neglects photon ISR & FSR, gluon FSR, fermion masses

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

- Measure cross-sections around M_Z via corrected event counts: $\sigma = \left(N_{\mathrm{sel}} - N_{\mathrm{bg}}\right)/\varepsilon_{\mathrm{sel}}L$

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

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



Other asymmetries (not in above cross section formula)

- Dependence of Z^0 production on helicities of initial state fermions (SLC) → *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 cosθ symmetric terms) expressed in Breit-Wigner form:

$$\sigma_{f\bar{f}}^{Z} = \sigma_{f\bar{f}}^{0} \cdot \frac{s \cdot \Gamma_Z^2}{\left(s - M_Z^2\right)^2 + s^2\Gamma_Z^2 / M_Z^2} \cdot \frac{1}{R_{\text{QED}}} \qquad \sigma_{f\bar{f}}^{0} = \frac{12\pi}{M_Z^2} \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

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 six measurements

- *Z* mass and width: M_Z, Γ_Z
- Hadronic pole cross section: σ^0_{had}
- Three leptonic ratios (use lepton-univ.): $R_\ell^0 = R_e^0 = \Gamma_{\text{had}} / \Gamma_{ee} = R_\mu^0 = R_\tau^0$
- Hadronic width ratios: R_b^0, R_c^0

Taken from LEP:
- precise $\sqrt{s}$
- high statistics

Include also SLD:
- higher effi./purity for heavy quarks

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": $\boldsymbol{R_{A,f}}$, $\boldsymbol{R_{V,f}}$

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

QCD corrections only affect final states with quarks

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

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

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

QED corrections similar: $R_{V,\mathrm{QED}} = R_{A,\mathrm{QED}} = R_{\mathrm{QED}} = 1 + \underbrace{\frac{3}{4} Q_f^2 \frac{\alpha(M_Z^2)}{\pi}}_{0.0019 \times Q_f^2} + \ldots$ ← What is this?

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

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

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

$$i\int d^4x\, e^{iqx} \langle 0 | T J^\mu_{\mathrm{em}}(x) \left(J^\nu_{\mathrm{em}}(0)\right)^\dagger | 0 \rangle = -\left(g^{\mu\nu} q^2 - q^\mu q^\nu\right) \prod\nolimits_\gamma (q^2)$$

Only vacuum polarisation "screens" electron charge

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)}$$

with:

$$\Delta\alpha(s) = -4\pi\alpha \,\mathrm{Re}\left[\prod\nolimits_\gamma(s) - \prod\nolimits_\gamma(0)\right] = \Delta\alpha_{\mathrm{lep}}(s) + \Delta\alpha_{\mathrm{had}}(s)$$

Leptonic $\Delta\alpha_{\mathrm{lep}}(s)$ 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*)

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

$$12\pi\, \mathrm{Im} \prod\nolimits_\gamma(s) = \frac{\sigma^{(0)}[e^+e^- \to \mathrm{hadrons}]}{\sigma^{(0)}[e^+e^- \to \mu^+\mu^-]} \equiv R(s)$$

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

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

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

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

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)

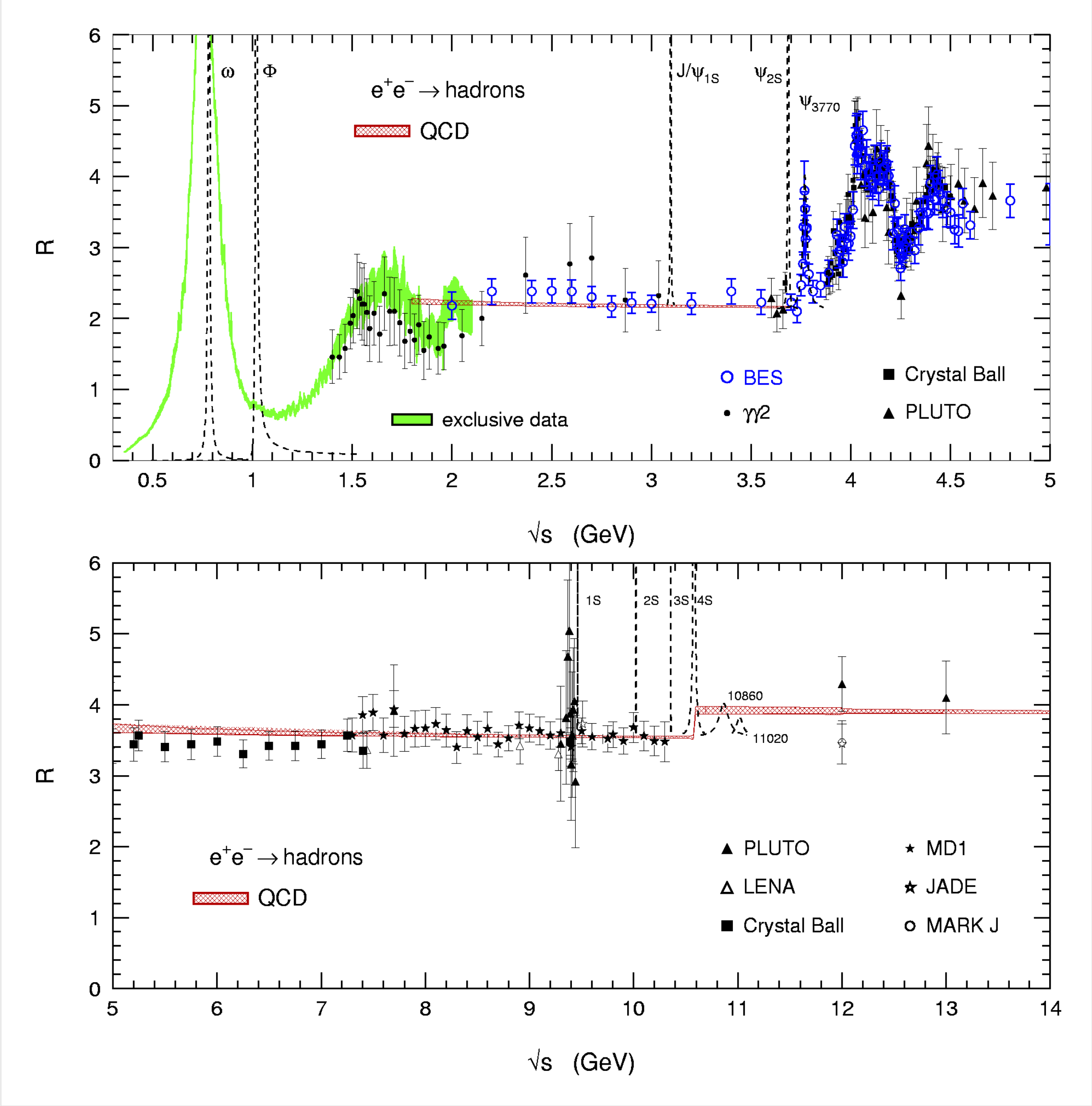
Traditionally separate:

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

Results [Hagiwara et al, PLB 649:, 73 (2007)]

$$\Delta\alpha(M_Z^2) = 0.03149769_{lep} + 0.02768(22)_{had\,(5)} - 0.000073(02)_{top}$$

$$\alpha^{-1}(M_Z^2) = 128.937 \pm 0.030$$



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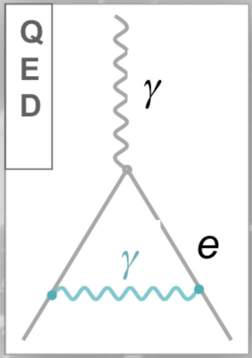
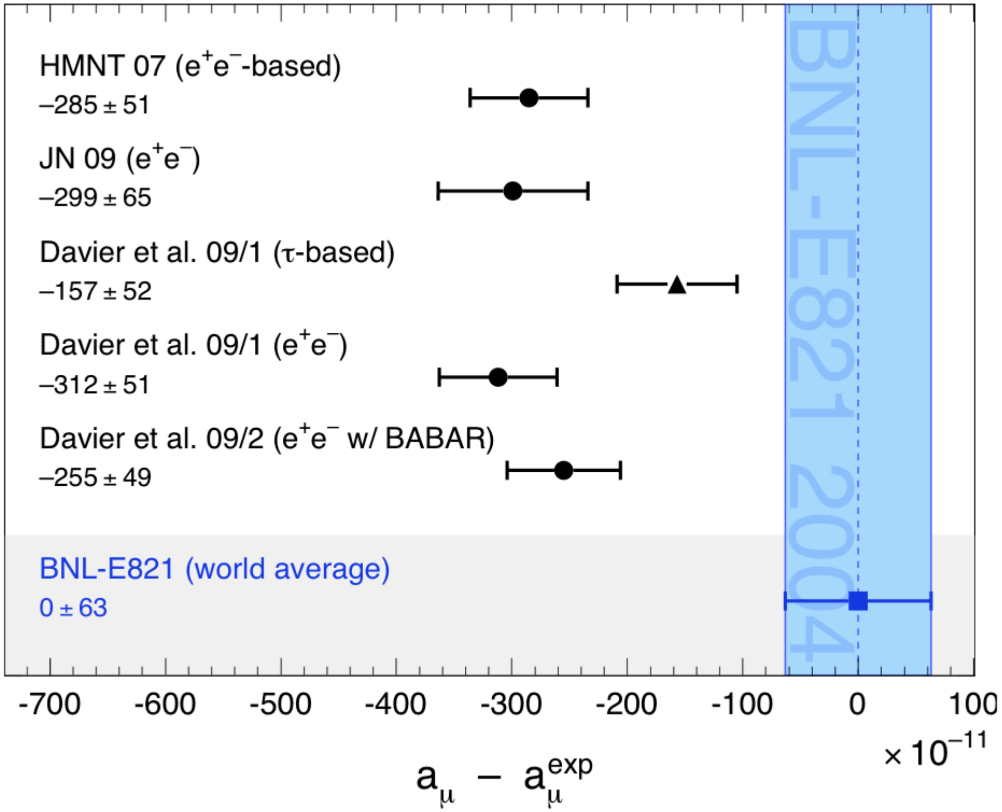


Muon magnetic moment: comparison between measurement (blue band) and predictions (dots)



The magnetic moment of the muon is predicted to a precision of several 10^{-6}, …

… but some tension exists …

Remember this slide ?

Standard Model prediction:

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Had-LO}} + a_\mu^{\text{Had-NLO}}$$

$$= (116\,591\,834 \pm 2 \pm 41 \pm 26) \times 10^{-11}$$

where: $a_\mu^{\text{QED}} = (116\,584\,718.09 \pm 0.15) \times 10^{-11}$

$$a_\mu^{\text{EW}} = (154 \pm 1_{\text{theo}} \pm 2_{M_H = 100...500\text{ GeV}}) \times 10^{-11}$$

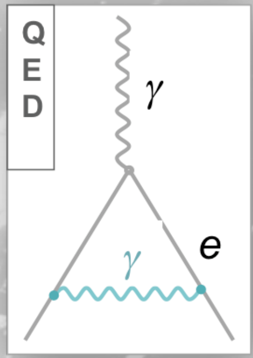
$$a_\mu^{\text{Had-LO}} = (6\,955 \pm 40_{\text{exp}} \pm 7_{\text{pQCD}}) \times 10^{-11}$$

$$a_\mu^{\text{Had-NLO}} = (7 \pm 1_{\text{NLO-disp}} \pm 26_{\text{LBLS}}) \times 10^{-11}$$

Experimental result (BNL):

$$a_\mu^{\text{exp}} = (116\,592\,089 \pm 54_{\text{stat}} \pm 33_{\text{syst}}) \times 10^{-11}$$

Deviation exp – SM: $(255 \pm 63 \pm 49) \times 10^{-11}$ ("3.2σ")



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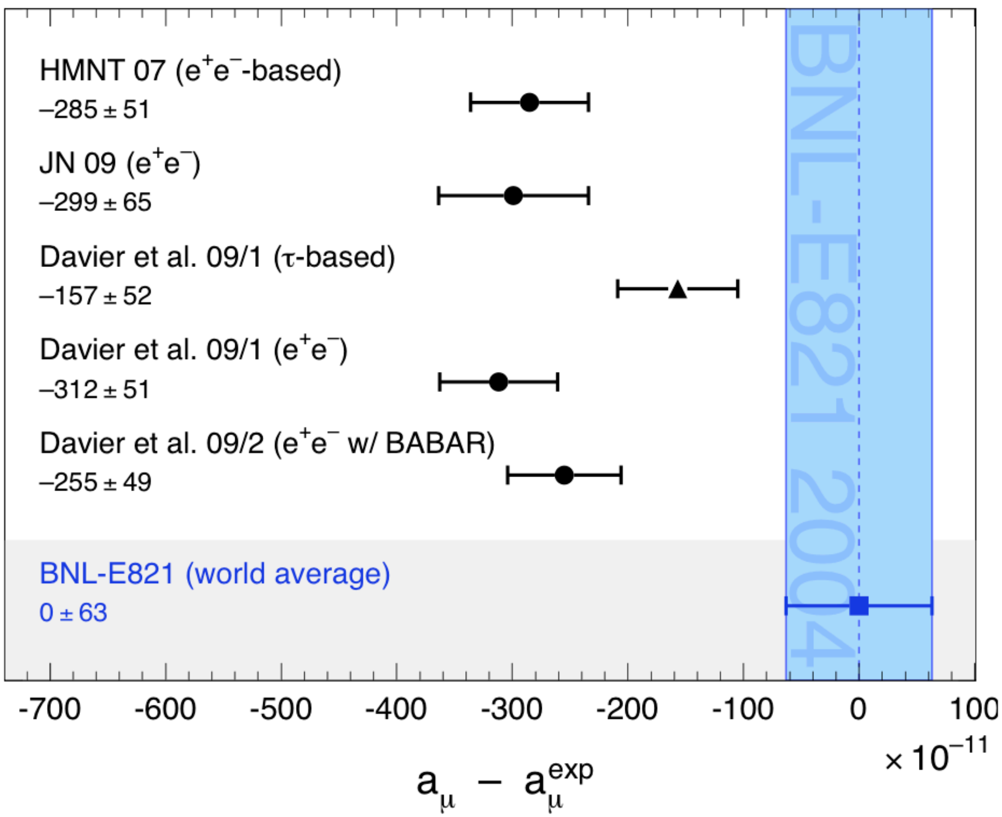

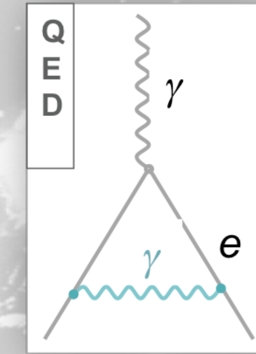

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(though much smaller due to $\alpha \ll \alpha_S$)

Measurements at the Z Pole

Asymmetry and polarisation – quantify parity violation

Distinguish vector and axial-vector couplings of the *Z* (*i.e.*, $\sin^2\theta^f_{\rm eff}$)

Convenient to use "asymmetry parameters":

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = 2\frac{g_{V,f}/g_{A,f}}{1+\left(g_{V,f}/g_{A,f}\right)^2}$$

dependent on $\sin^2\theta^f_{\rm eff}$: $\frac{\mathrm{Re}(g_{V,f})}{\mathrm{Re}(g_{A,f})} = 1-4\left|Q_f\right|\sin^2\theta^f_{eff}$

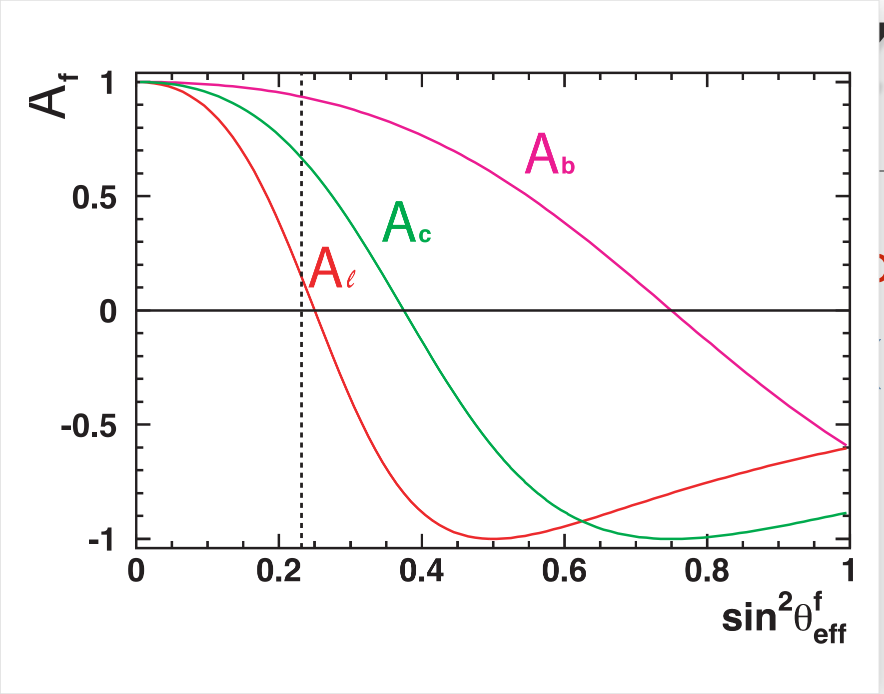
Via *final state (FS) angular distribution* in unpolarised scattering (LEP)

- Forward-backward asymmetries: $A^f_{\rm FB} = \frac{N_F - N_B}{N_F + N_B}$, $A^{0,f}_{\rm FB} = \frac{3}{4}A_e A_f$
- LEP measurements: $A^{0,l}_{\rm FB}$, $A^{0,c}_{\rm FB}$, $A^{0,b}_{\rm FB}$

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

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

Me … Pole



Asymmetry and … on

Distinguish vecto … *i.e.*, $\sin^2\theta^f_{\text{eff}}$)

Convenient to us

$$A_f = \frac{g^2_{L,f} - g^2_{R,f}}{g^2_{L,f} + g^2_{R,f}} \quad \frac{\mathrm{Re}(g_{V,f})}{\mathrm{Re}(g_{A,f})} = 1 - 4\left|Q_f\right|\sin^2\theta^f_{eff}$$

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

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- LEP measurements: $A^{0,l}_{\text{FB}}$, $A^{0,c}_{\text{FB}}$, $A^{0,b}_{\text{FB}}$

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: $A^0_{\text{LR}} = A_e$, $A^{0,f}_{\text{LRFB}} = \frac{3}{4}A_f$

Measurements at the Z Pole

Asymmetry and polarisation – quantify parity violation

Distinguish vector and axial-vector couplings of the Z (*i.e.*, $\sin^2\theta^f_{\rm eff}$)

Convenient to use "asymmetry parameters":

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = 2\frac{g_{V,f}/g_{A,f}}{1+\left(g_{V,f}/g_{A,f}\right)^2}$$

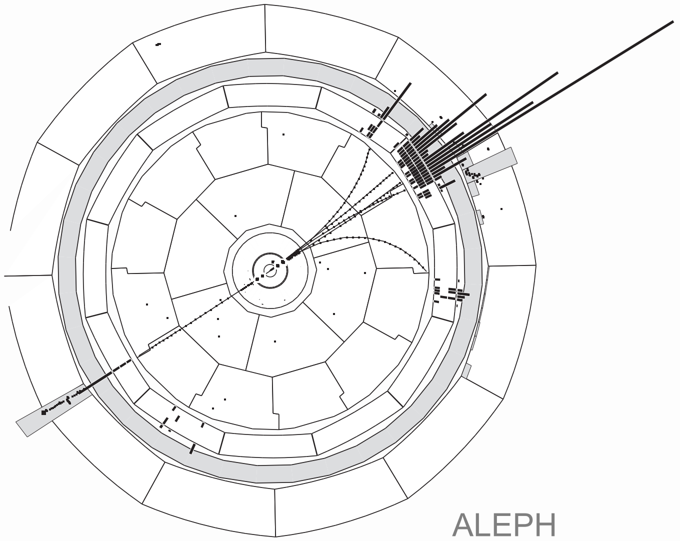
dependent on $\sin^2\theta^f_{\rm eff}$: $\dfrac{\mathrm{Re}(g_{V,f})}{\mathrm{Re}(g_{A,f})} = 1-4\left|Q_f\right|\sin^2\theta^f_{eff}$

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

Measurements at the Z Pole

Asymmetry and polarisation – quantify parity violation

Distinguish vector and axial-vector couplings of the Z (*i.e.*, $\sin^2\theta^f_{\rm eff}$)

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$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = 2\frac{g_{V,f}/g_{A,f}}{1+\left(g_{V,f}/g_{A,f}\right)^2}$$

dependent on $\sin^2\theta^f_{\rm eff}$: $\dfrac{\mathrm{Re}(g_{V,f})}{\mathrm{Re}(g_{A,f})} = 1 - 4\left|Q_f\right|\sin^2\theta^f_{eff}$

The measured asymmetries are corrected for QED radiation, γ–Z interference to give "pole" quantities $^{(0)}$.

In case of e^+e^- final state, must also take into account t-channel scattering.

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)

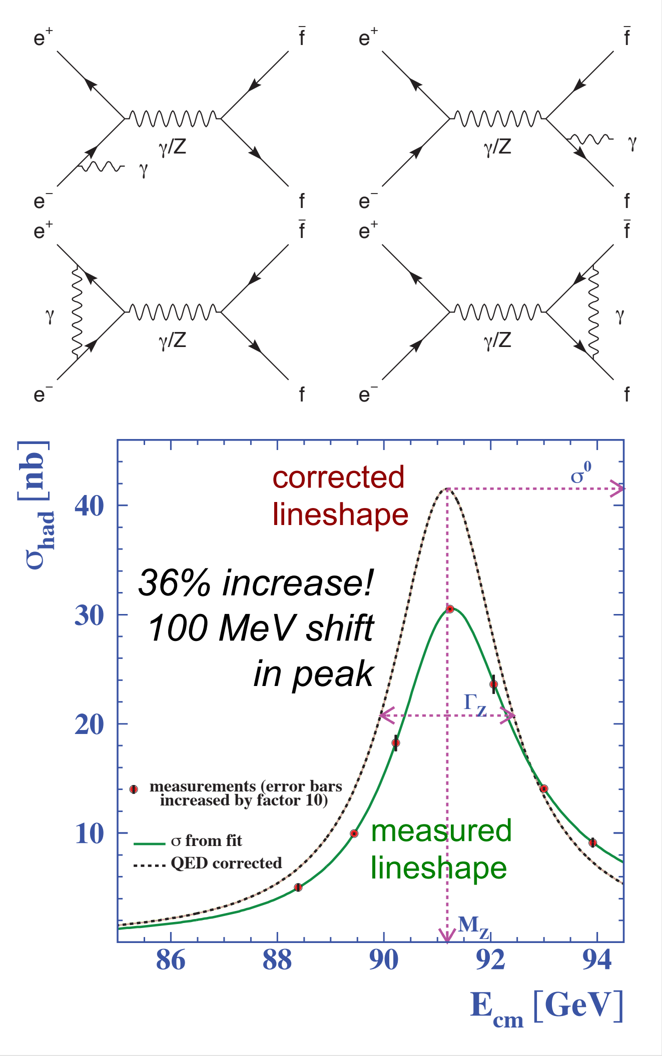
$$\sigma(s) = \int_{4m_f^2/s}^{1} dz \cdot H_{\mathrm{QED}}^{\mathrm{tot}}(z,s) \cdot \sigma(zs)$$

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^0_{had}

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

Summary – experimental results on the Z pole

Experimental Input

Parameter	Input value	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP / SLC
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	SLC
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP / SLC
R^0_b	0.21629 ± 0.00066	LEP / SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP

Total cross-sections around M_Z

- Measured by: M_Z, Γ_Z, $\sigma^0_{\rm had}$, R_l^0, R_c^0, R_b^0
- Sensitive to the total coupling strength of the Z to fermions

Asymmetries on the Z pole

- Measured by: $A_{\rm FB}^{0,l}$, $A_{\rm FB}^{0,b}$, $A_{\rm FB}^{0,c}$, A_l, A_c, A_b, $\sin^2\theta^l_{\rm eff}\,(Q_{\rm FB})$
- Sensitive to the ratio of the Z^0 vector to axial-vector couplings (*i.e.* $\sin^2\theta_{\rm eff}$)

And additional observables in fit

- M_W is subject to rad. corr. via: $\Delta r = \Delta\alpha(M_Z) - \Delta\rho + \ldots$ (higher orders)
- m_t due to its large loop corrections

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)]
- M_W and Γ_W: LEP + Tevatron (incl. Moriond-09 result from D0)
  [ADLO, hep-ex/0612034] [D0 Conference Note 5893-CONF] [CDF, Phys Rev. D77, 112001 (2008)]
  [CDF, Phys. Rev. Lett. 100, 071801 (2008)] [CDF+D0, Phys. Rev. D 70, 092008 (2004)]
- m_t: latest Tevatron average [arXiv:0903.2503]
- m_c, m_b: world averages [PDG, J. Phys. G33,1 (2006)]
- $\Delta\alpha_{had}(M_Z)$: [K. Hagiwara et al., Phys. Lett. B649, 173 (2007)] + rescaling mechanism to account for α_s dependency
- Direct Higgs searches at LEP and Tevatron (incl. Moriond-09 Tevatron average)
  [ADLO: Phys. Lett. B565, 61 (2003)] [CDF+D0: arXiv:0903.4001]

Not considered: results on $\sin^2\theta_{eff}$ from

- NuTeV: unclear theoretical uncertainties from QCD effects
  (NLO corrections, nuclear effects of the bound nucleon PDFs)
- APV, fixed target polarised Möller scattering: present experimental accuracy too low

Experimental Input

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$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP

Parameter	Input value	
M_H [GeV] $^{(\circ)}$	Likelihood ratios	LEP & Tevatron
M_W [GeV]	80.399 ± 0.023	LEP & Tevatron
Γ_W [GeV]	2.098 ± 0.048	LEP & Tevatron
$\overline{m}_c$ [GeV]	1.25 ± 0.09	
$\overline{m}_b$ [GeV]	4.20 ± 0.07	
m_t [GeV]	173.1 ± 1.3	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2769 ± 22	
$\alpha_s(M^2_Z)$	$-$	
$\delta_{\rm th} M_W$ [MeV]	$[-4,4]_{\rm theo}$	
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7,4.7]_{\rm theo}$	
$\delta_{\rm th}\rho^f_Z$ $^{(\dagger)}$	$[-2,2]_{\rm theo}$	
$\delta_{\rm th}\kappa^f_Z$ $^{(\dagger)}$	$[-2,2]_{\rm theo}$	

Correlations for observables from Z lineshape fit

	M_Z	Γ_Z	$\sigma^0_{\rm had}$	R^0_ℓ	$A^{0,\ell}_{\rm FB}$
M_Z	1	-0.02	-0.05	0.03	0.06
Γ_Z		1	-0.30	0.00	0.00
$\sigma^0_{\rm had}$			1	0.18	0.01
R^0_ℓ				1	-0.06
$A^{0,\ell}_{\rm FB}$					1

Correlations for heavy-flavour observables at Z pole

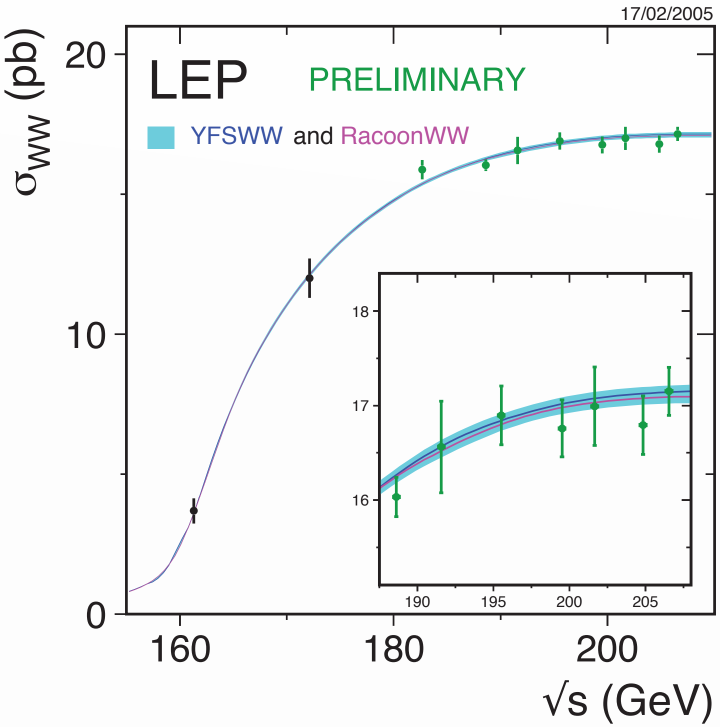
	$A^{0,c}_{\rm FB}$	$A^{0,b}_{\rm FB}$	A_c	A_b	R^0_c	R^0_b
$A^{0,c}_{\rm FB}$	1	0.15	0.04	-0.02	-0.06	0.07
$A^{0,b}_{\rm FB}$		1	0.01	0.06	0.04	-0.10
A_c			1	0.11	-0.06	0.04
A_b				1	0.04	-0.08
R^0_c					1	-0.18

Precision Measurement of the *W* mass

Results from LEP-2:

- 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 "colour reconnection" systematics in hadronic channel (35 MeV)
  - Combination: $M_W = (80.376 \pm 0.025 \pm 0.022)$ GeV

4 × 700 pb^{-1} taken for $\sqrt{s}$ = 161–209 GeV between 1996 and 2000 at LEP-2



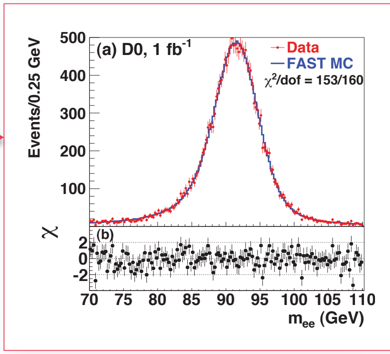
Results from Tevatron:

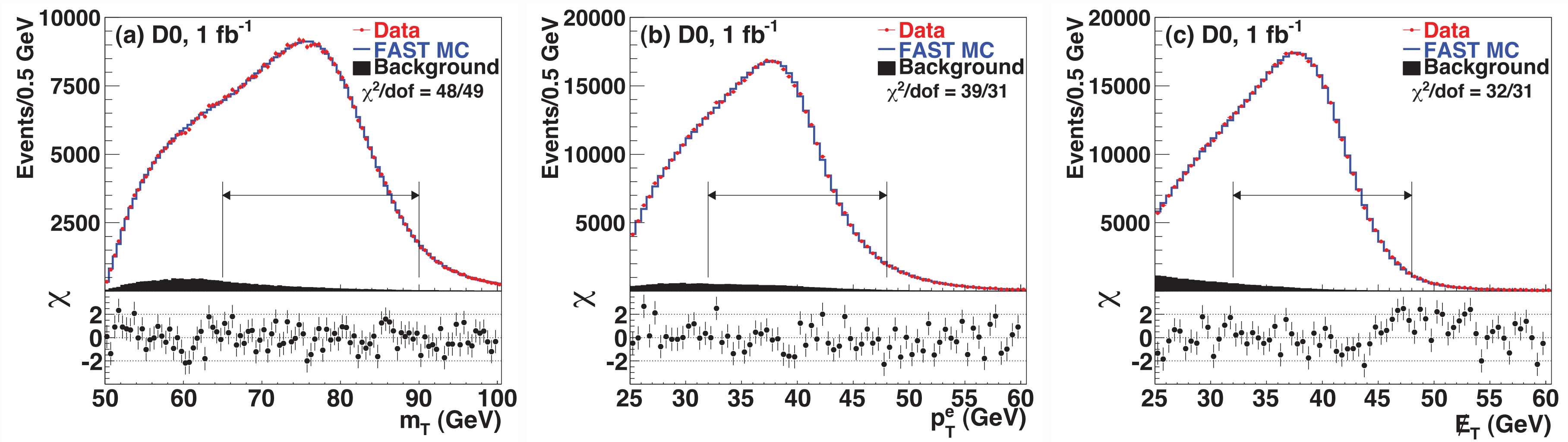
- Using leptonic *W* decays
  - M_W from template fits to the transverse mass or transverse momentum of lepton
  - Extremely challenging, systematics dominated measurement (energy calibration)
  - Combination (2009): $M_W = (80.420 \pm 0.031)$ GeV

Precision Measurement of the *W* mass

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

- Analysis relies on energy calibration with $Z \to ee$
- Result: M_W = (80.401 ± 0.021 ± 0.038) GeV
- Greatly deserves the label *"precision measurement"*



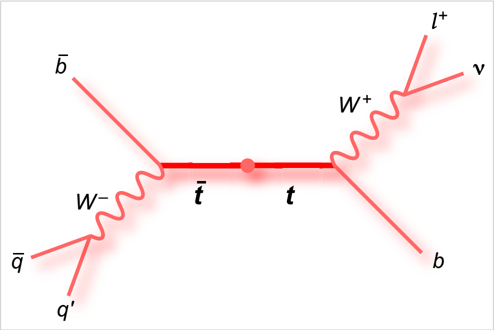


The (a) m_T , (b) $p^e{}_T$, and (c) $E_{T,\text{miss}}$ distributions for data and fastmc simulation with backgrounds. The χ values are shown below each distribution where $\chi_i = [N_i - (\text{fastmc}_i)]/\sigma_i$ for each point in the distribution, N_i is the data yield in bin i and only the statistical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

Measurement of the top mass

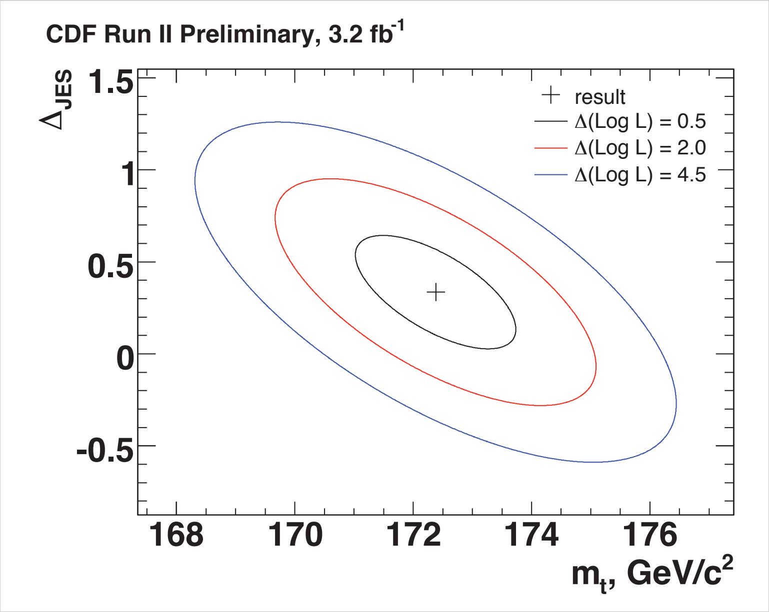
Top quark mass is measured in di-lepton (4%), lepton-jets (30%), and jets-jets (46%) modes

- 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



The lepton-jets channel provides most precise m_t measurment

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



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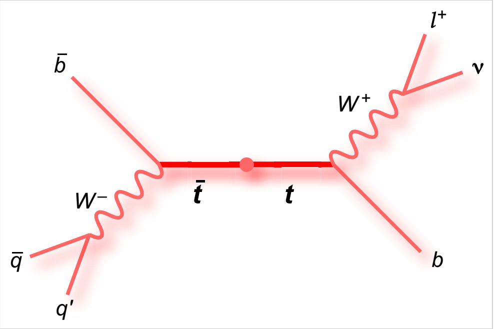

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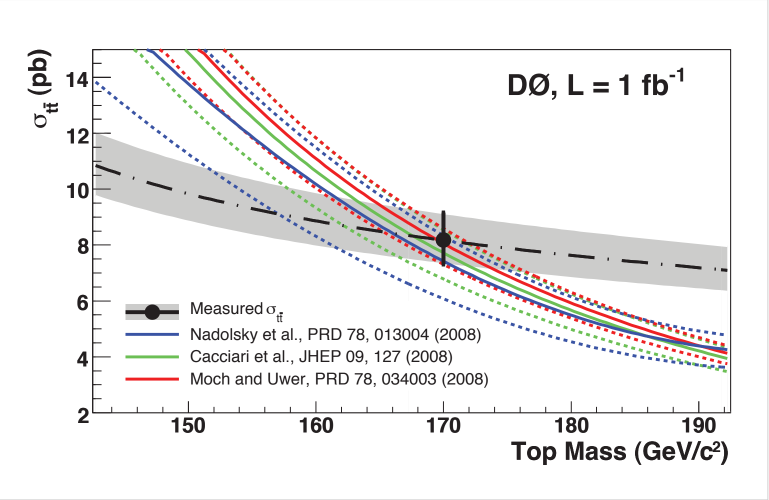
Fit method: parameterise templates depending on top mass and JES for sensitive variables (e.g., $M_{\text{jet-jet}}$, $M_{letp\text{-}jet}$, …), construct and maximise overall likelihood function

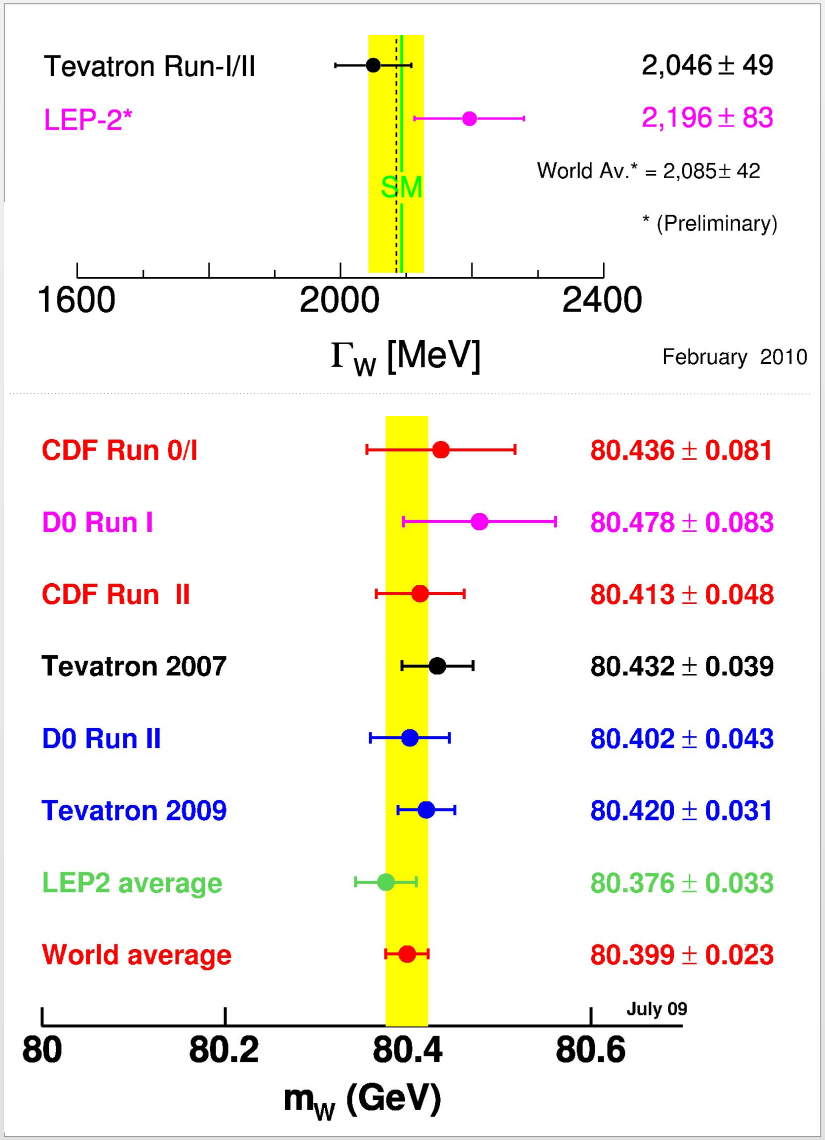
Can also extract m_t from top cross section measurement

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

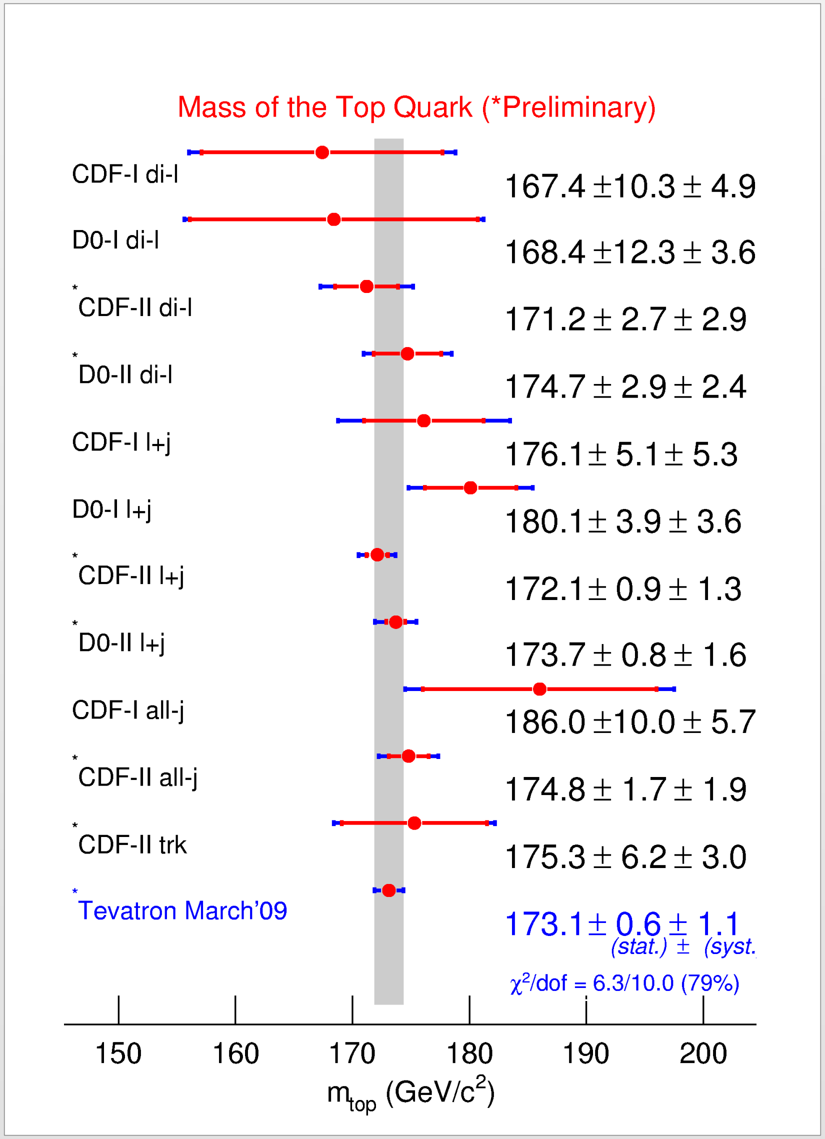


2009 Γ_W, M_W (left) and m_{top} (right) world averages

[CDF + D0, up to 1 fb–1, 0908.1374, width: D0 Note 6041-CONF]



[CDF + D0, 3.6 fb^{-1}, arXiv:0903.2503]



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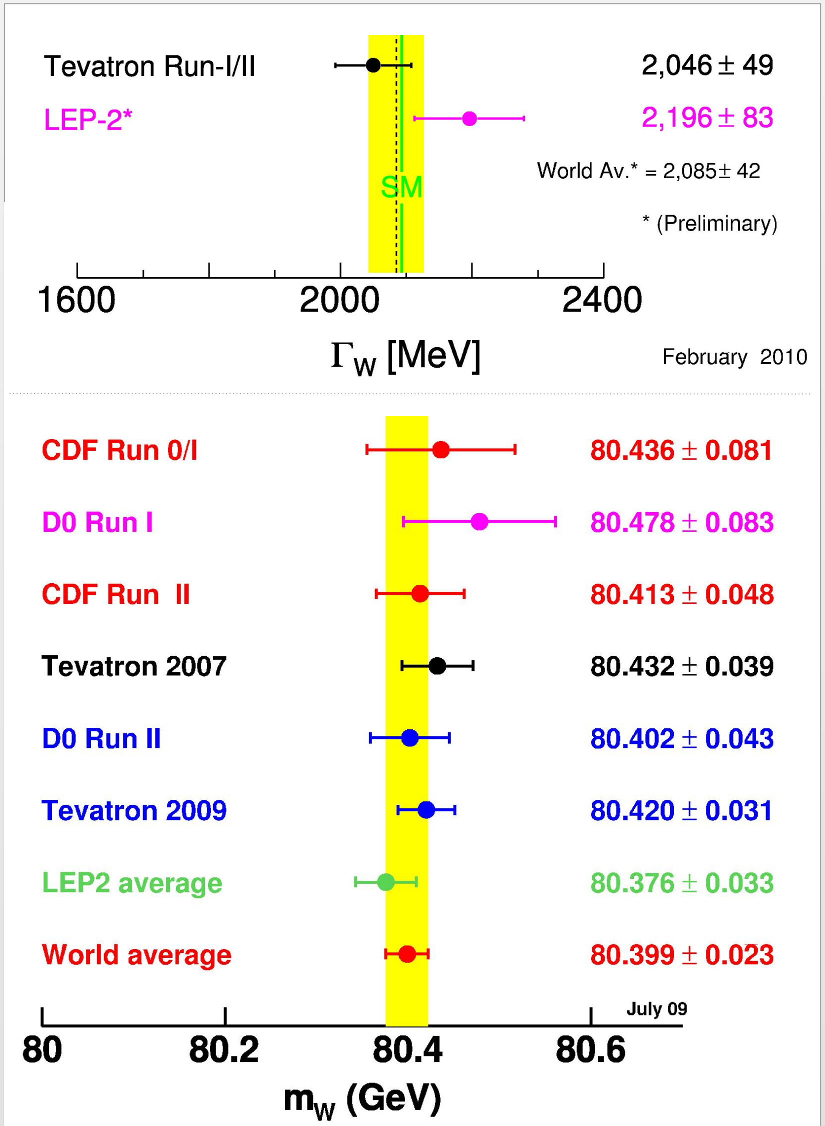
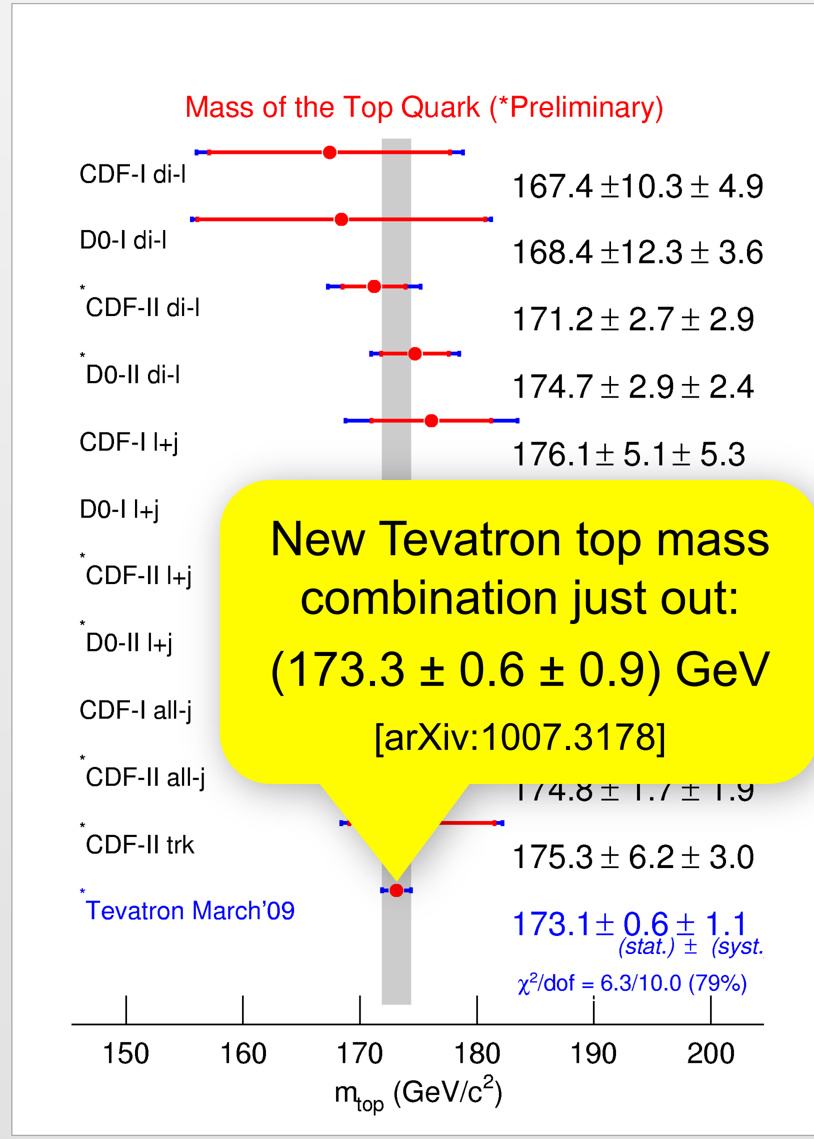


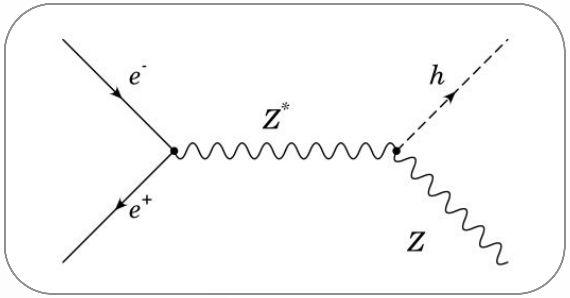
[CDF + D0, 3.6 fb^{-1}, arXiv:0903.2503]



Constraints from Direct Higgs Searches

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

- *ee → ZH (H → bb, ττ)*
  [ADLO: Phys. Lett. B565, 61 (2003)]

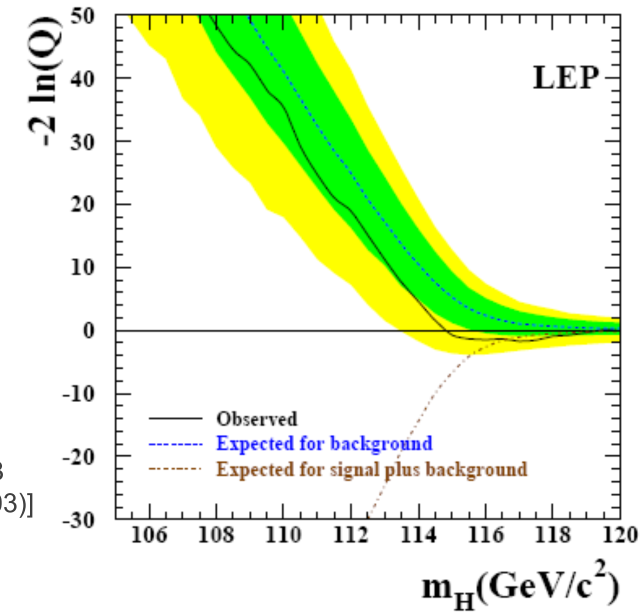


Tevatron: *see yesterday’s lecture*

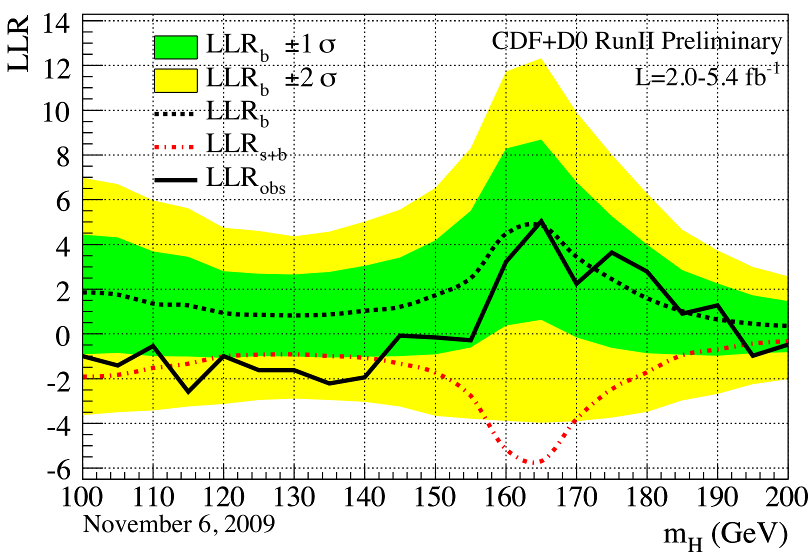
Statistical interpretation in global fit: *two-sided CL_{S+B}*

- Experiments measure test statistics LLR = –2ln*Q*, where $Q = L_{S+B} / L_B$
- LLR is transformed by experiments into CL_{S+B} using pseudo-MC experiments
- We transform one-sided CL_{S+B} into a two-sided CL_{S+B} (measure *deviation* from SM !)
- Contribution to χ^2 estimator obtained via inverse error function: $\Delta\chi^2 = \mathrm{Erf}^{-1}\left(1 - CL_{S+B}^{2\text{-sided}}\right)$
- Alternative treatments:
  - Use one-sided CL_{S+B}: however, different interpretation – want SM Higgs (not *any* Higgs)
  - Directly use $\Delta\chi^2 \approx$ LLR: Bayesian interpretation, lacks pseudo-MC information

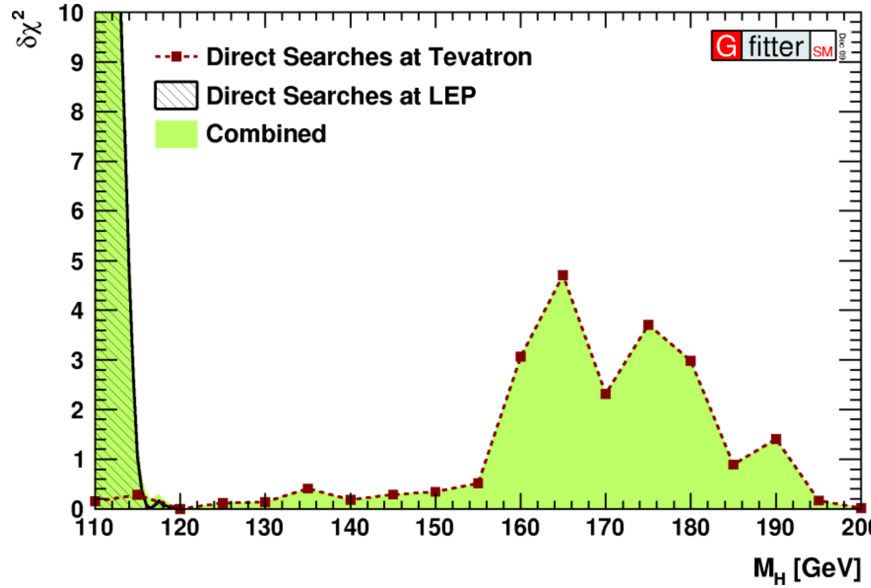
Direct Higgs Searches



[ADLO:
Phys. Lett. B
565, 61 (2003)]



Combined $\delta\chi^2$ input to EW fit:



Note: "hypothesis-only" test

(like the –2lnQ curves delivered by the collaborations)

- Procedure tests only the M_H under consideration
- It neglects that a given SM signal hypothesis entails background hypotheses

  → if SM Higgs is found at a certain M_H other values of M_H are excluded
- Effect expected to be small today, but relevant once the Higgs is discovered.

The Global Electroweak Fit

Fit parameters – unknown SM parameters are floating in fit

Naïve set of free parameters relevant for the electroweak analysis:

- Coupling constants: electromagnetic (α), weak (G_F), strong (α_S)
- Boson masses: M_γ, M_Z, M_W, M_H
- Fermion masses: m_f with $f = e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, u, c, t, d, s, b$

Simplification: massless neutrinos : $m_{\nu e} = m_{\nu\mu} = m_{\nu\tau} = 0$

Simplification from electroweak unification:

- Massless photon: $M_\gamma = 0$
- Can express M_W as a function of M_Z and the couplings α and G_F

Further simplification by fixing parameters with insignificant uncertainties compared to sensitivity of the fit

- G_F, and leptonic contribution to running of α

The Global Electroweak Fit

Fit parameters – unknown SM parameters are floating in fit

Masses of leptons and light quarks are small and/or sufficiently well known
→ uncertainties are negligible in the fit

- Masses are fixed to world-averages from PDG
- Except for the running charm, bottom and top masses → m_t strongest impact on fit !

List of remaining parameters in the SM fit:
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$, $\alpha_S(M_Z)$, M_Z, M_H, $\overline{m}_c$, $\overline{m}_b$, m_t

State-of-the art calculations, in particular:

- M_W and $\sin^2\theta^f_{\rm eff}$: 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]

The Global Electroweak Fit

Fit parameters – theoretical uncertainties are also floating parameters

Fit minimises test statistics: $\chi^2 = -2\ln L$

The likelihood function "*L*" is a product of contributions that

- Measure the agreement between $x_{\text{theo}}(y_{\text{mod}})$ and x_{exp}
- Expresses prior knowledge of some of the y_{mod} parameters (if available)

The fit shown in the following treats errors as follows:

- Statistical and systematic **experimental errors** obey **Gaussian** likelihood functions
- **Theoretical errors** have bound uniform likelihoods → **allowed ranges**

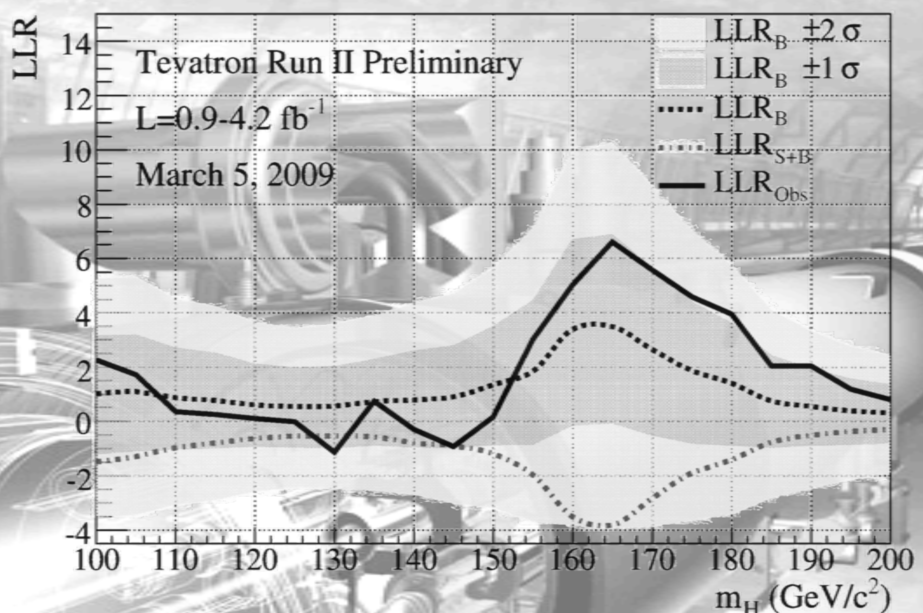
Most important theoretical uncertainties included in the SM fit:

- Uncertainty on M_W from missing higher order corrections: $\delta M_W = 4 - 6$ MeV
- Uncertainty on $\sin^2\theta^l_{\text{eff}}$ from missing higher order corrections: $\delta\sin^2\theta^l_{\text{eff}} = 4.7\cdot 10^{-5}$

Fit Results(*)

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: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1974^{+0.0146}_{-0.0159}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	$2.4954^{+0.0016}_{-0.0013}$	$2.4954^{+0.0008}_{-0.0012}$
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.472 ± 0.001	41.469 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.018	20.741 ± 0.018	20.718 ± 0.027
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01638 ± 0.0002	0.01624 ± 0.0002	0.01618 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1478 ± 0.0010	0.1472 ± 0.0009	–
A_c	0.670 ± 0.027	–	$0.6682^{+0.00045}_{-0.00044}$	$0.6679^{+0.00043}_{-0.00037}$	$0.6679^{+0.00044}_{-0.00034}$
A_b	0.923 ± 0.020	–	0.93469 ± 0.00009	$0.93464^{+0.00006}_{-0.00007}$	$0.93463^{+0.00006}_{-0.00007}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0741^{+0.0006}_{-0.0005}$	0.0737 ± 0.0005	0.0738 ± 0.0005
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1036 ± 0.0007	0.1032 ± 0.0006	$0.1037^{+0.0004}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17225 ± 0.00006	0.17226 ± 0.00006	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21579^{+0.00004}_{-0.00006}$	0.21577 ± 0.00005	0.21577 ± 0.00005
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23145^{+0.00011}_{-0.00016}$	0.23151 ± 0.00011	$0.23148^{+0.00013}_{-0.00010}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$82.8^{+30.2[+75.2]}_{-23.2[-41.5]}$	$119.1^{+13.4[+37.9]}_{-4.0[-4.9]}$	$82.8^{+30.2[+75.2]}_{-23.2[-41.5]}$
M_W [GeV]	80.399 ± 0.023	–	$80.384^{+0.014}_{-0.015}$	$80.370^{+0.008}_{-0.010}$	$80.365^{+0.009}_{-0.026}$
Γ_W [GeV]	2.098 ± 0.048	–	2.092 ± 0.001	2.091 ± 0.001	2.092 ± 0.001
$\overline{m}_c$ [GeV]	1.25 ± 0.09	yes	1.25 ± 0.09	1.25 ± 0.09	–
$\overline{m}_b$ [GeV]	4.20 ± 0.07	yes	4.20 ± 0.07	4.20 ± 0.07	–
m_t [GeV]	173.1 ± 1.3	yes	173.2 ± 1.2	173.6 ± 1.2	$177.9^{+11.2}_{-3.5}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2769 ± 22	yes	2772 ± 22	2764 ± 22	2733^{+57}_{-46}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	0.1193 ± 0.0028	0.1193 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	4.7	0.8	–
$\delta_{\rm th}\rho^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2	–
$\delta_{\rm th}\kappa^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2	–

Correlation coefficients of free fit parameters

Parameter	$\ln M_H$	$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$	M_Z	$\alpha_S(M_Z^2)$	m_t	$\overline{m}_c$	$\overline{m}_b$
$\ln M_H$	1	-0.395	0.113	0.041	0.309	-0.001	-0.006
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$		1	-0.006	0.101	-0.007	0.001	0.003
M_Z			1	-0.019	-0.015	-0.000	0.000
$\alpha_S(M_Z^2)$				1	0.021	0.011	0.043
m_t					1	0.000	-0.003
$\overline{m}_c$						1	0.000

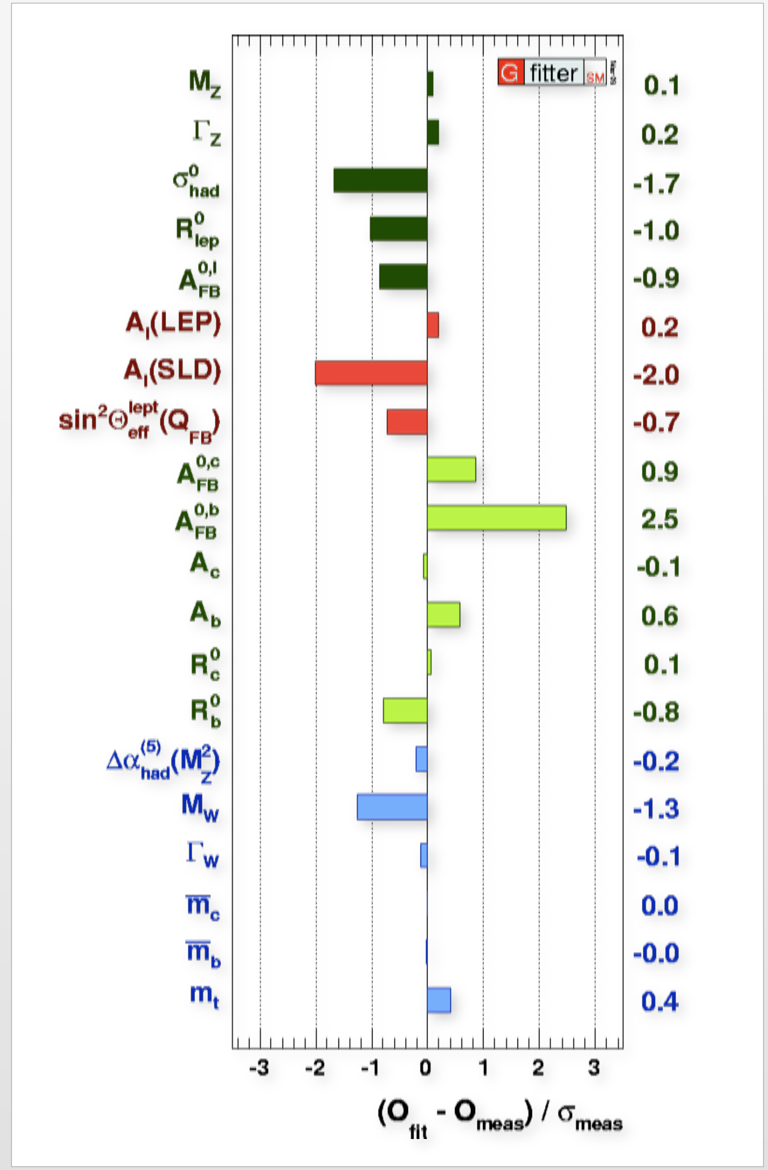
Goodness-of-Fit

Goodness-of-fit:

- *Standard fit*: $\chi^2_{min} = 16.4 \rightarrow \text{Prob}(\chi^2_{min},13) = 0.23$
- *Complete fit*: $\chi^2_{min} = 17.9 \rightarrow \text{Prob}(\chi^2_{min},14) = 0.21$

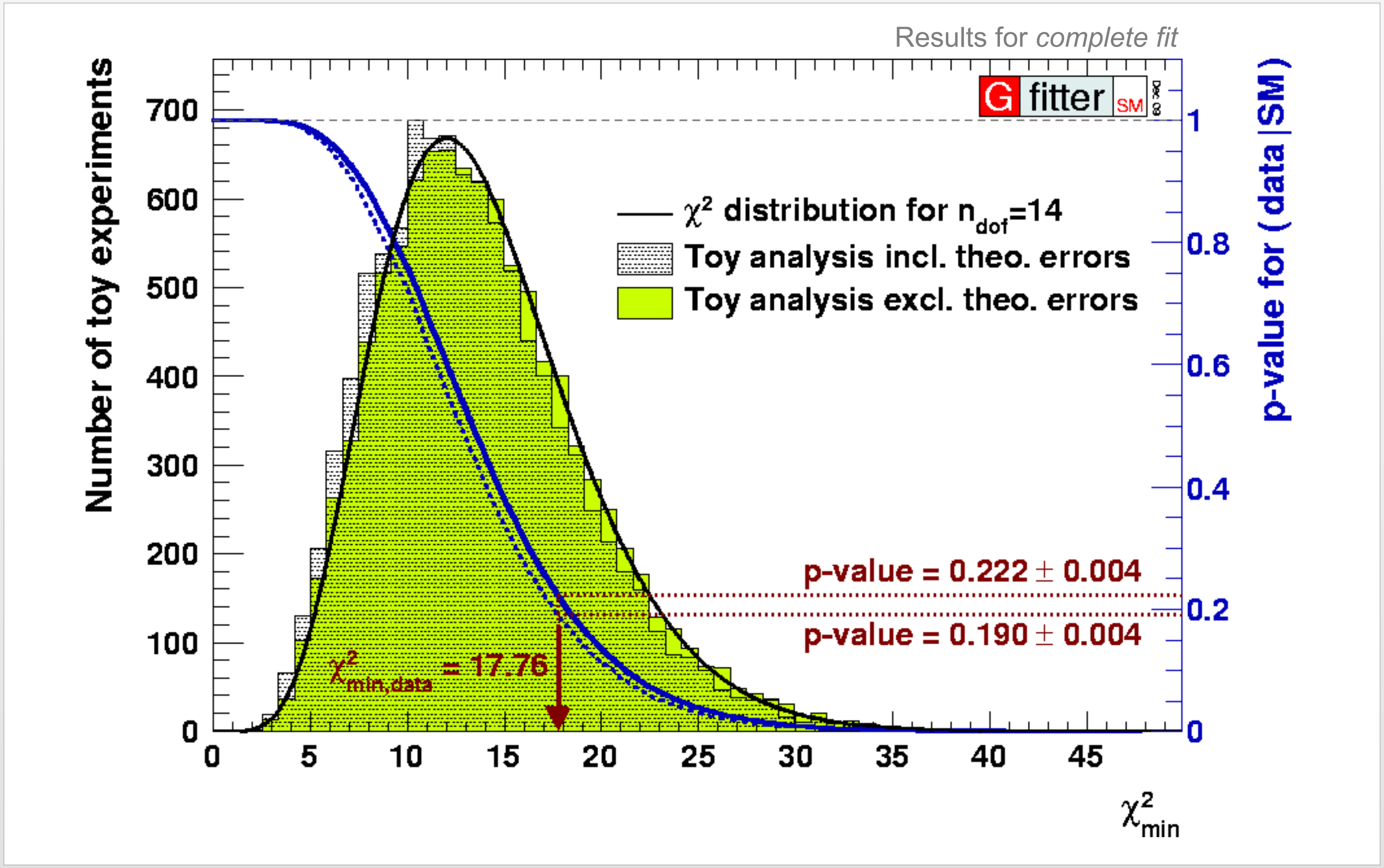
Pull values for complete fit (right figure →)

- No individual pull exceeds 3σ
- FB(b) asymmetry largest contributor to χ^2_{min}
- Small contributions from M_Z, $\Delta\alpha^{had}(M_Z)$, 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 = 0.20 ± 0.01–0.02$_{theo}$



Higgs Mass Constraints

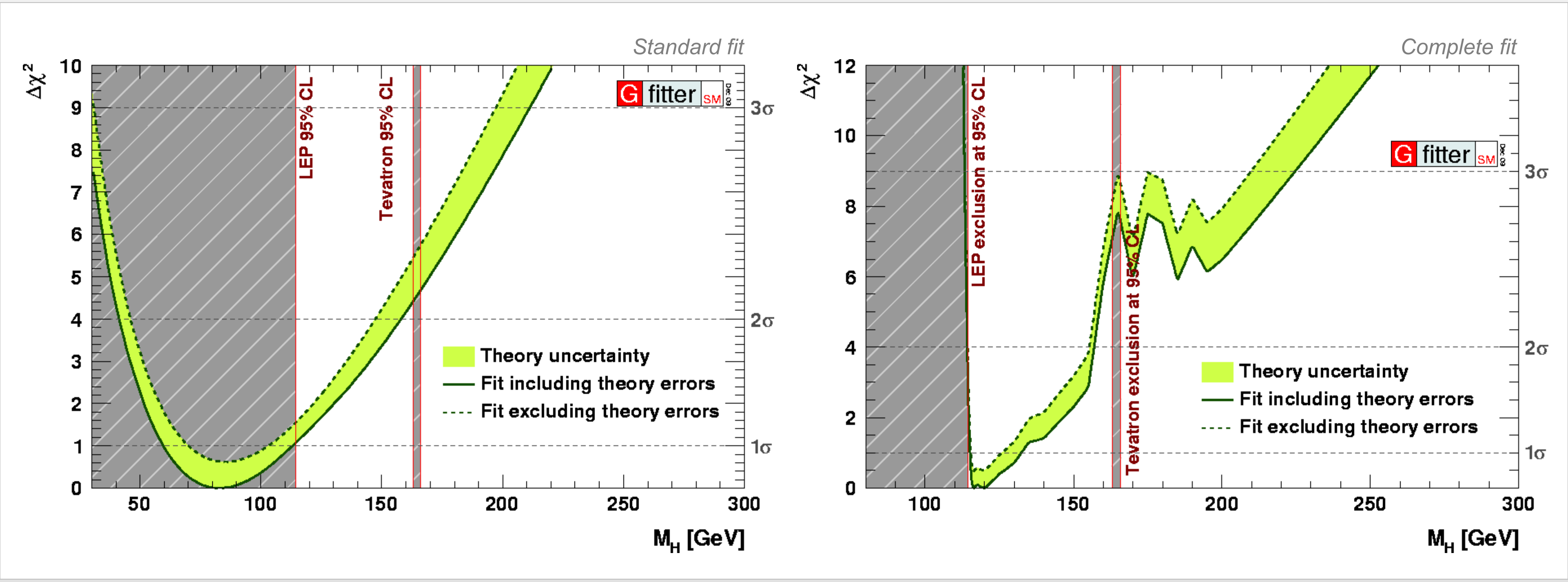
M_H from *Standard fit*:

- Central value ±1σ: $M_H = 83^{+30}_{-23}$ GeV
- 2σ interval: [42, 158] GeV

M_H from *Complete fit*:

- Central value ±1σ: $M_H = 119^{+13}_{-4.0}$ GeV
- 2σ interval: [114, 157] GeV

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



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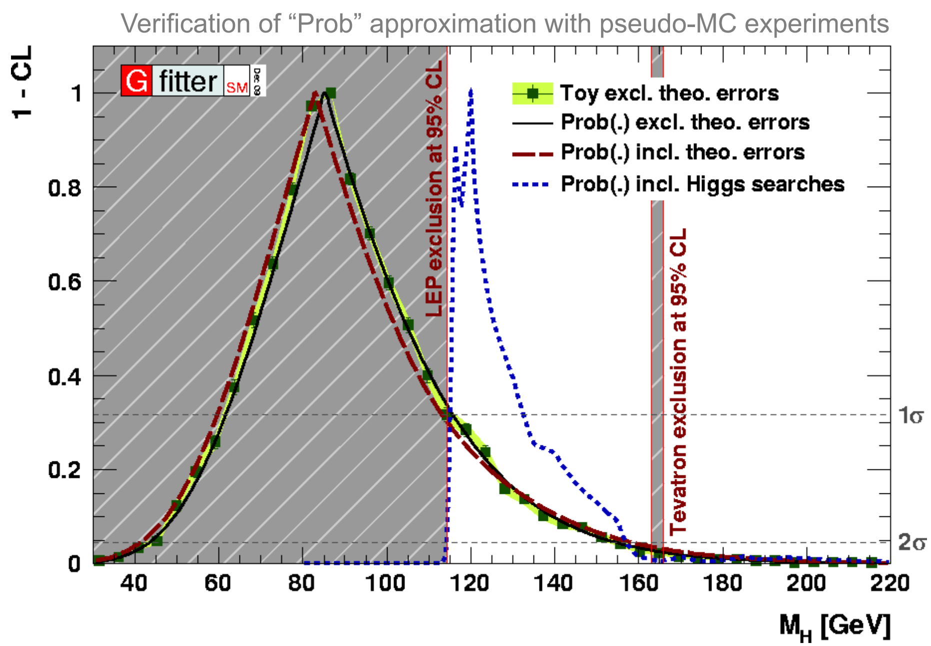

Verify Gaussian Prob($\Delta\chi^2$,1) approximation

- Fix M_H, perform two fits and calculate Prob($\Delta\chi^2(M_H) = \chi^2_{min}(M_H) - \chi^2_{min}$,1)
- Generate pseudo experiments ("toy MC") using fitted values for M_H with experimental errors
- For each toy experiment perform two fits and compute $\Delta\chi^2_{toy}(M_H)$ exactly as in real data
- Compute 1−CL at M_H by integrating normalised $\Delta\chi^2_{toy}(M_H)$ distribution from $\Delta\chi^2(M_H)$ to infinity
- **Assumes that $\Delta\chi^2_{toy}(M_H)$ distribution is independent of nuisance parameters !**

Higgs Mass Constraints

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M_H from *Complete fit*:

- Central value ±1σ: $M_H = 119^{+13}_{-4.0}$ GeV
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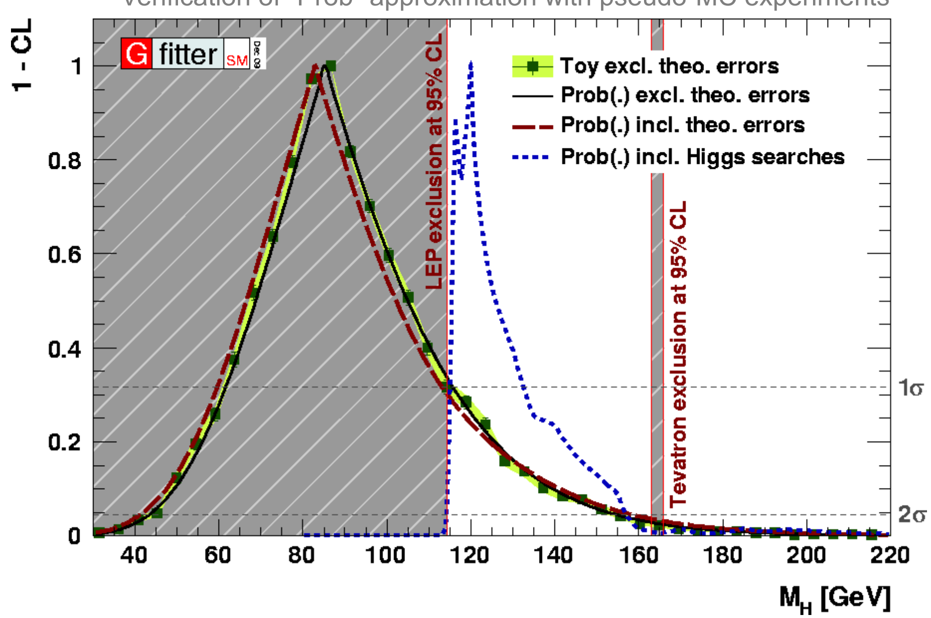
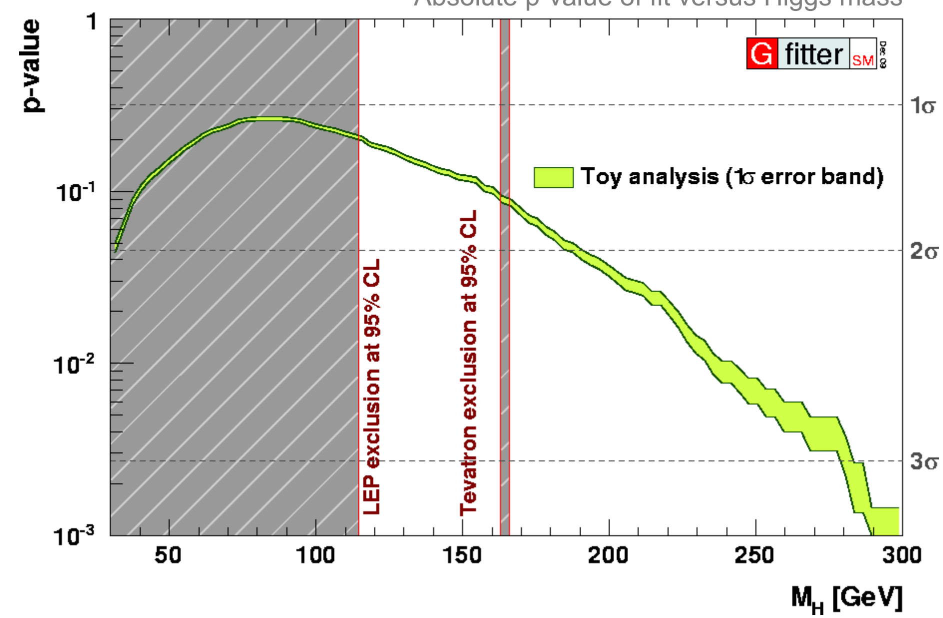
Curve gives the probability of wrongly rejecting SM hypothesis assuming a certain value for M_H

Verification of “Prob” approximation with pseudo-MC experiments



Absolute p-value of fit versus Higgs mass



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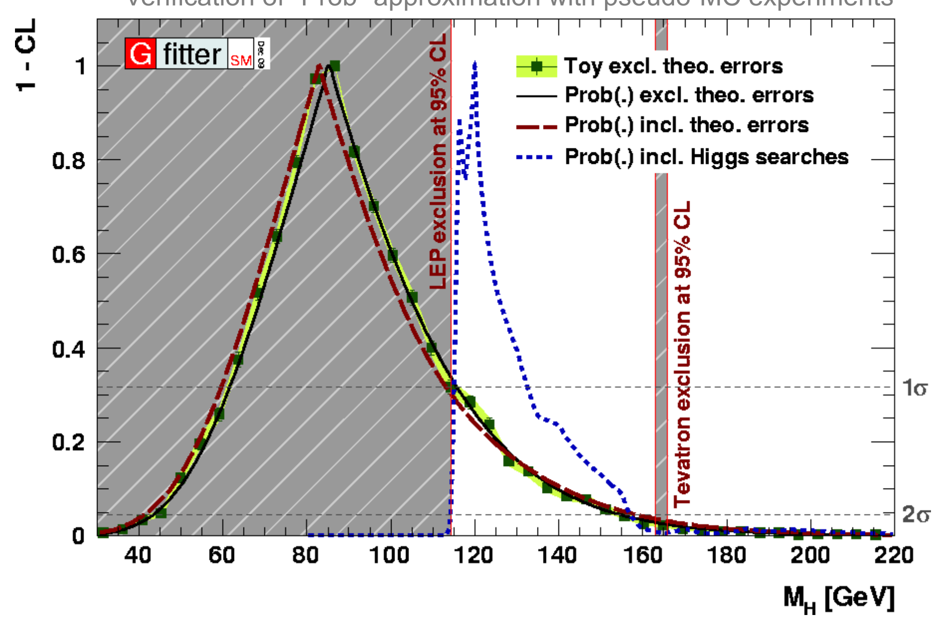
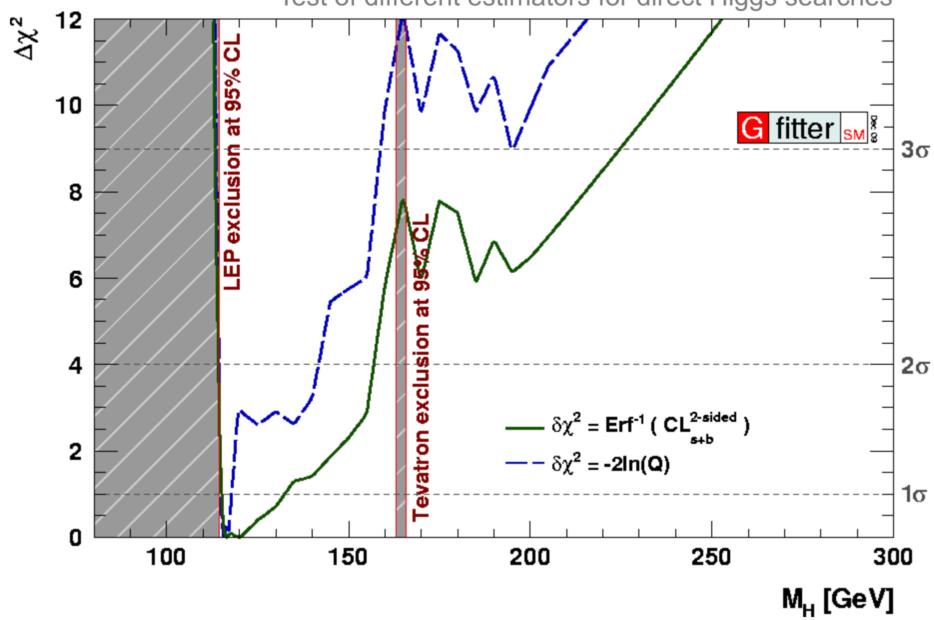


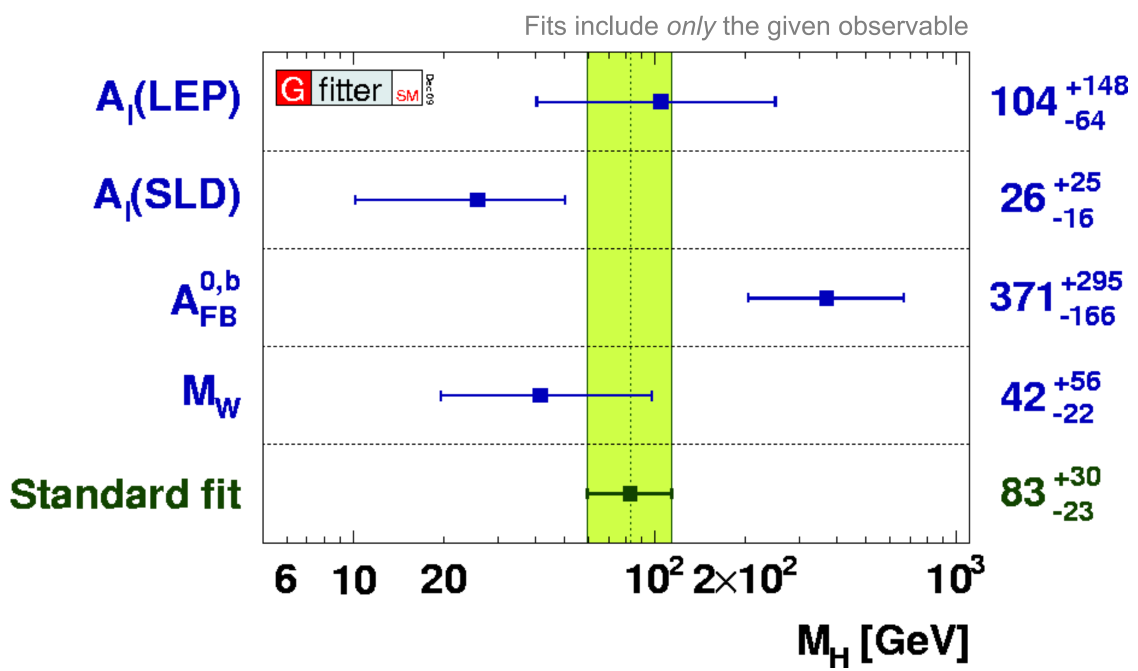
Test of different estimators for direct Higgs searches



Higgs Mass Constraints

Known tension between $A^{0,b}_{FB}$ 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% (2.5σ)



Top Mass

Quadratic sensitivity to m_{top}

- *Standard fit*: $m_{top} = 177.2^{+10.5}_{-7.8}$ GeV
- *Complete fit*: $m_{top} = 177.9^{+11.2}_{-3.5}$ GeV

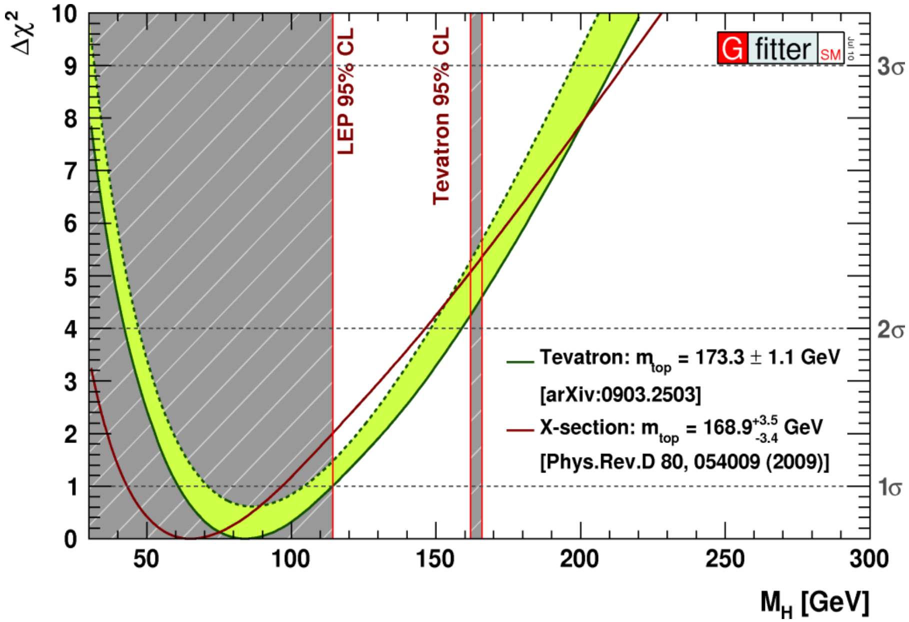
Tevatron average: (173.1 ± 1.3) GeV

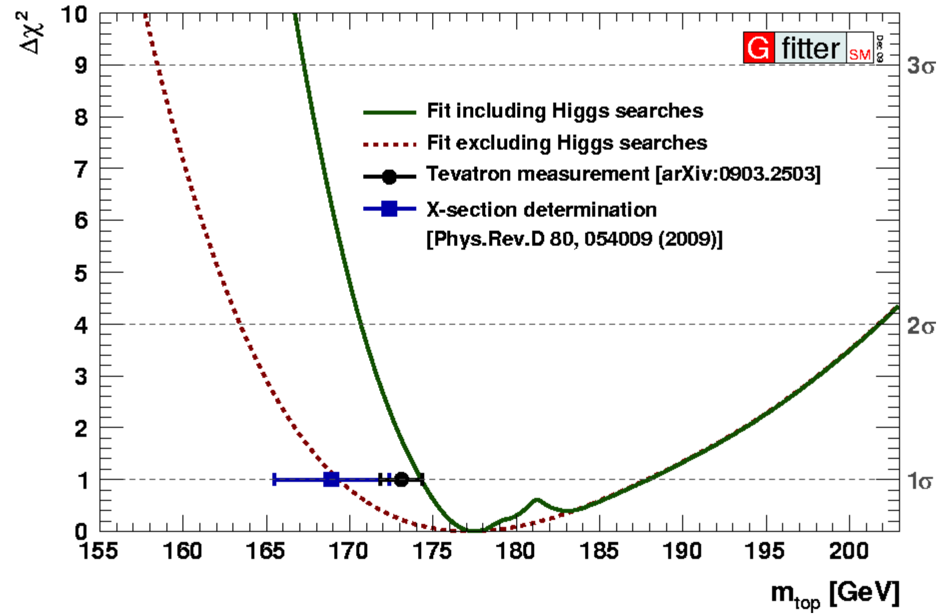
→ What is this mass? Pole mass? "MC" mass?

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

Reasons: floating Higgs mass and its positive correlation with m_t

What happens if we use the cross section mass in the fit ?





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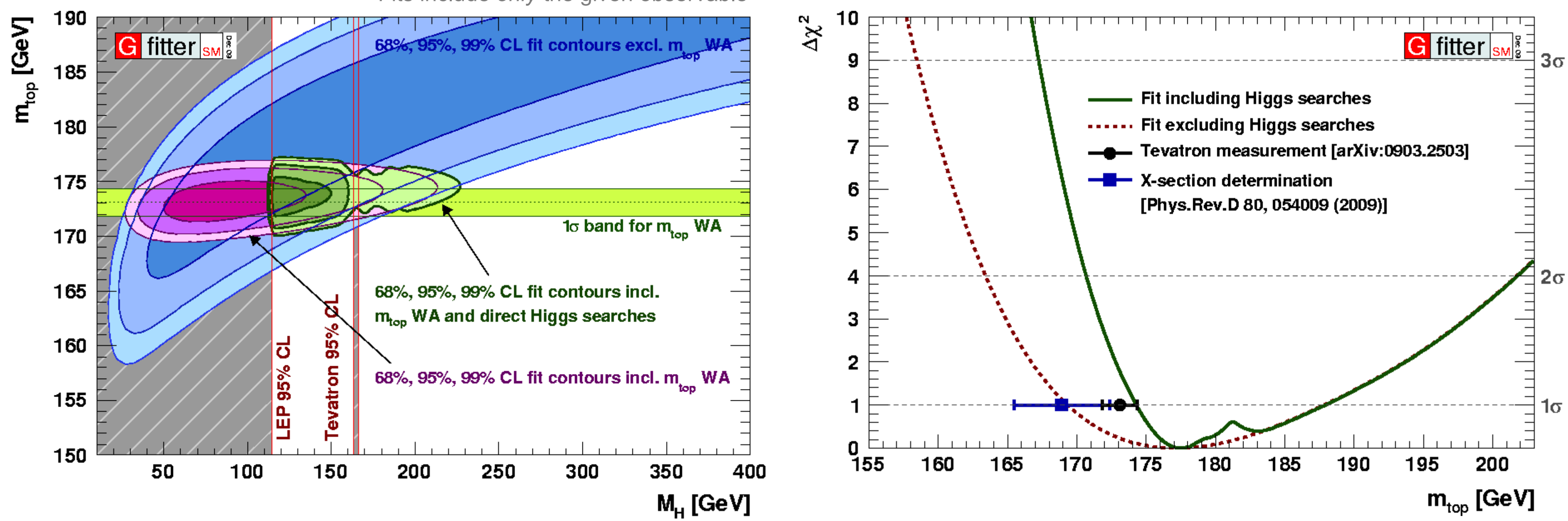
For Standard fit with free m_{top} find: $m_H = 116^{+184}_{-61}$ GeV

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

Reasons: floating Higgs mass and its positive correlation with m_t

Fits include *only* the given observable



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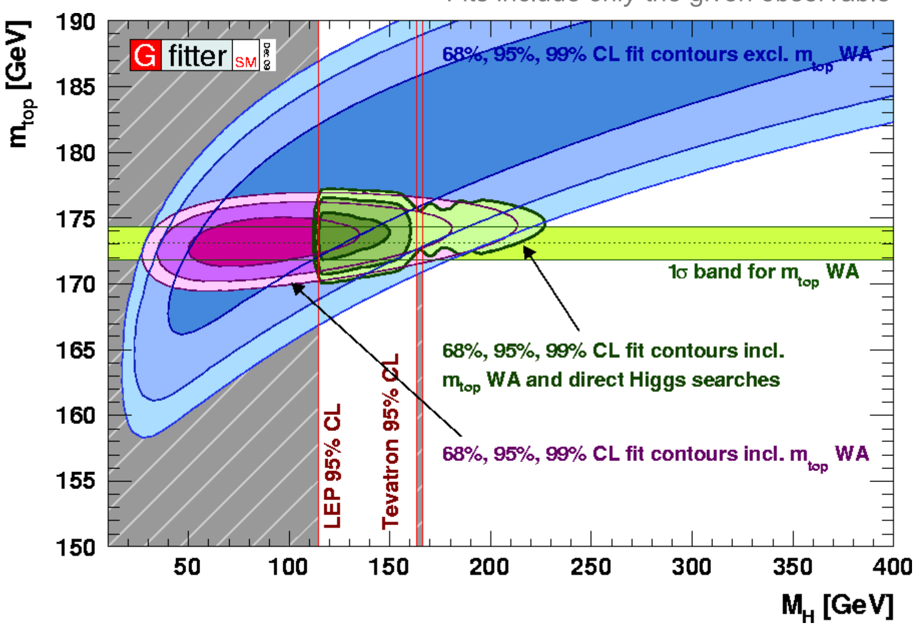
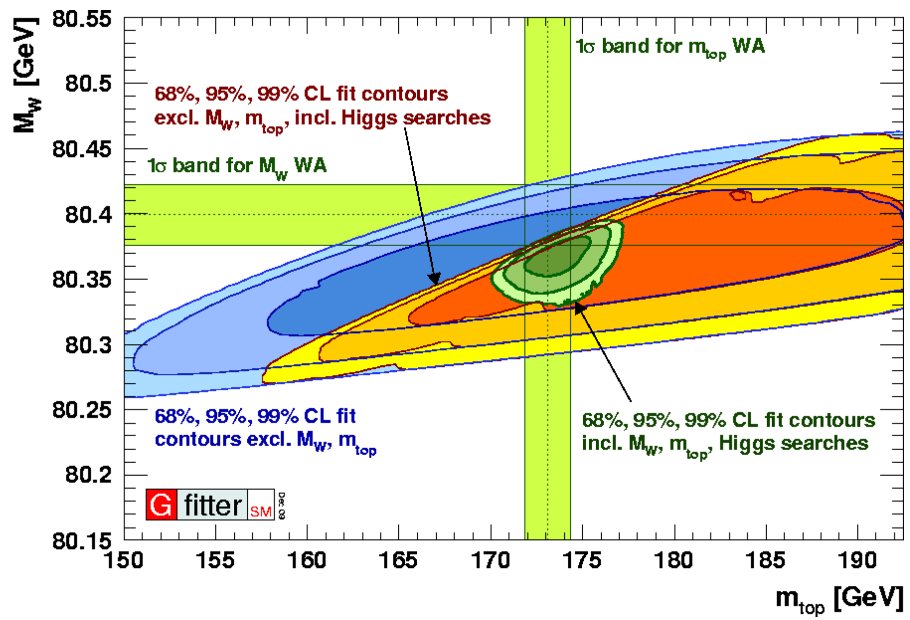
Fit (*i.e.* excluding the Higgs searches and the respective measurements)

Fit + Higgs searches

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

Fits include *only* the given observable





$\Delta\alpha_{\text{had}}(M_Z)$

Strong sensitivity to $\Delta\alpha_{\text{had}}(M_Z)$

- *Complete fit*: $\Delta\alpha^{(5)}_{\text{had}}(M_Z^2) = (273.3\,^{+5.7}_{-4.6}) \cdot 10^{-4}$

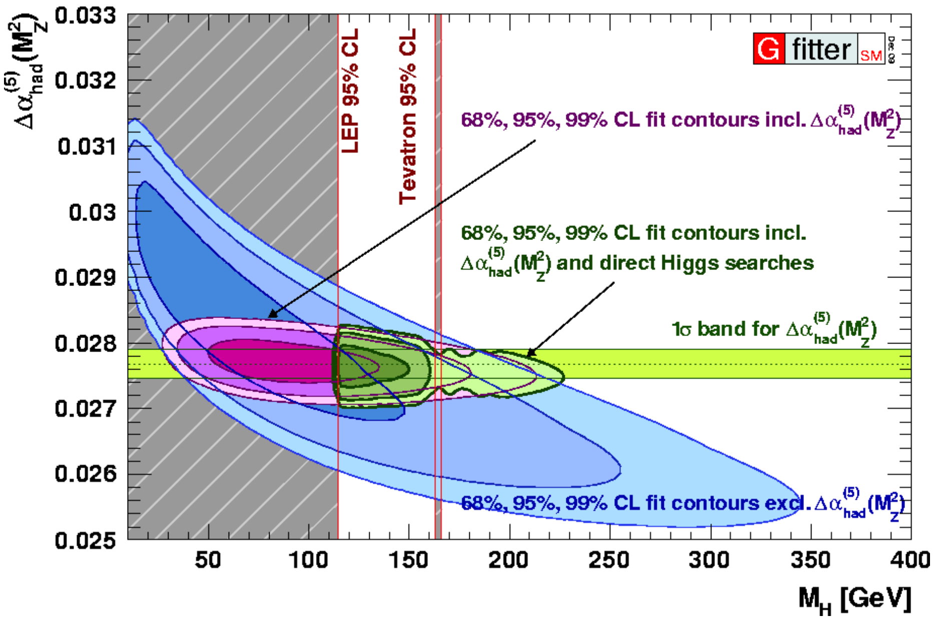
Phenomenological value: $(277.2 \pm 2.2)\ 10^{-4}$

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

Fit + Higgs searches

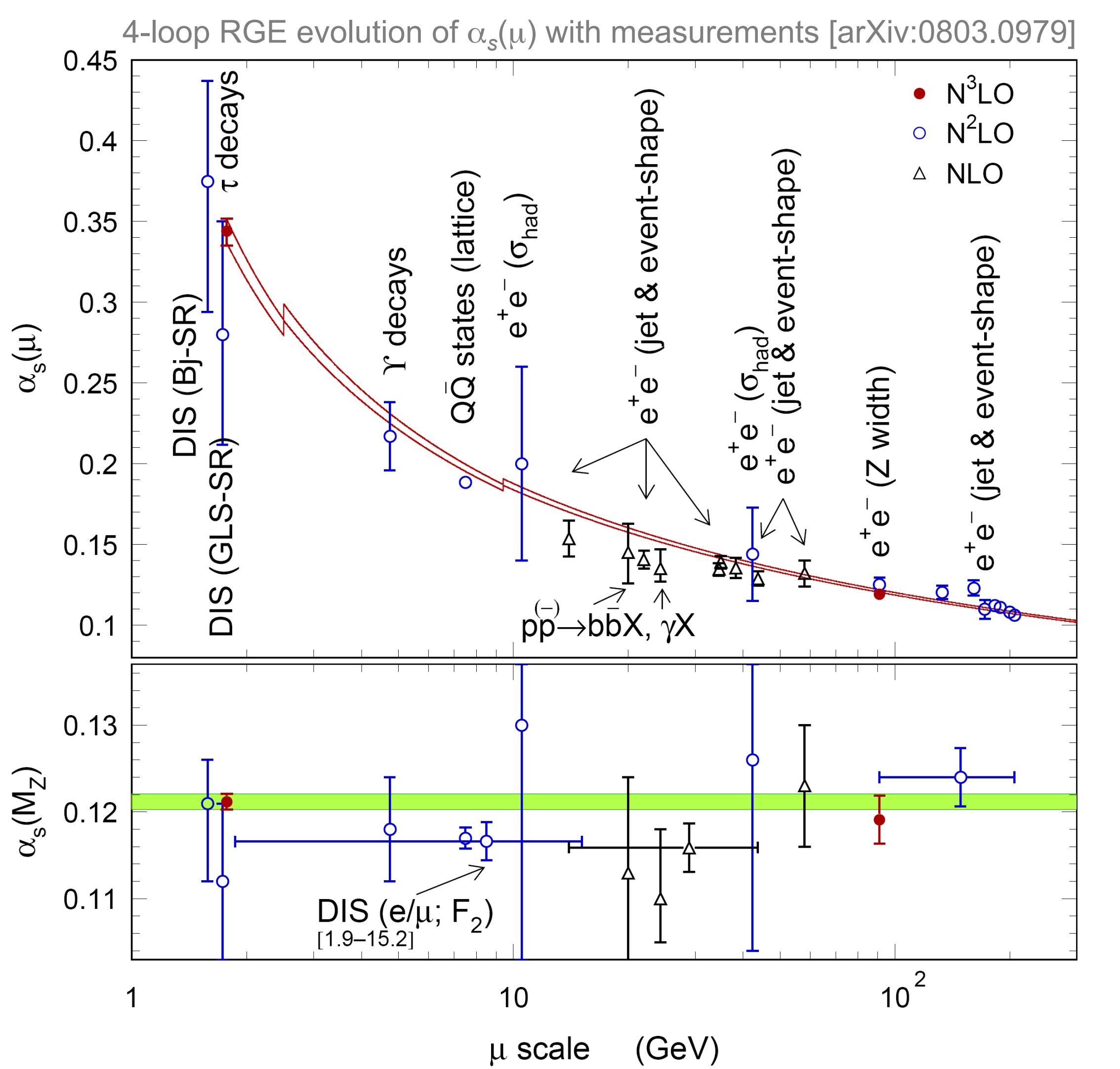
Fit + Higgs searches + direct measurements
→ best knowledge of SM

Fits include *only* the given observable



- The structures reflect presence of local minima in ($\Delta\chi^2$ vs. M_H)-plot
- Today's precision in m_t and $\Delta\alpha_{\text{had}}(M_Z)$ sufficient for the EW fit

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 $a_S^5(M_Z)$ and massive terms of order/beyond $a_S^4(M_Z)$]
- Excellent agreement with N³LO result from hadronic τ decays
  [M. Davier et al., arXiv:0803.0979]

  $\alpha_s(M_Z) = 0.1212 \pm 0.0005_{exp} \pm 0.0008_{theo} \pm 0.0005_{evol}$
- Best current test of asymptotic freedom property of QCD !

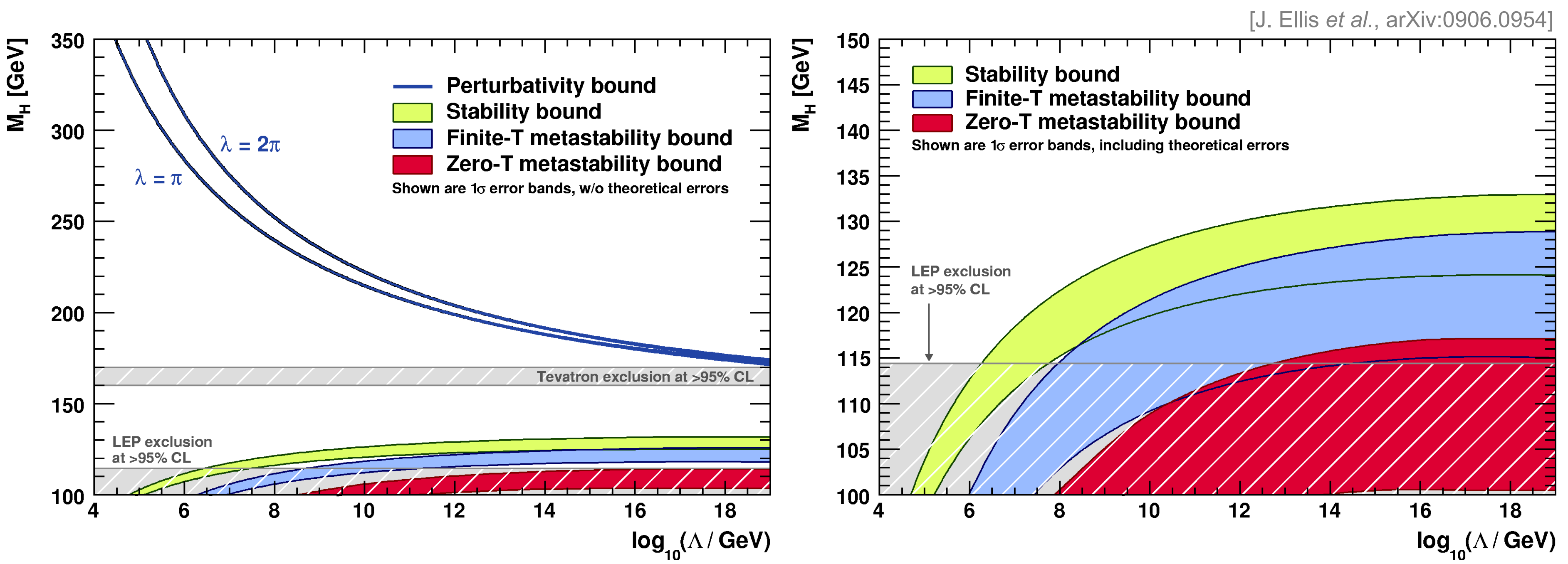
The Fate of the Standard Model

Driving the SM to M_{Planck}

Remember, 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**

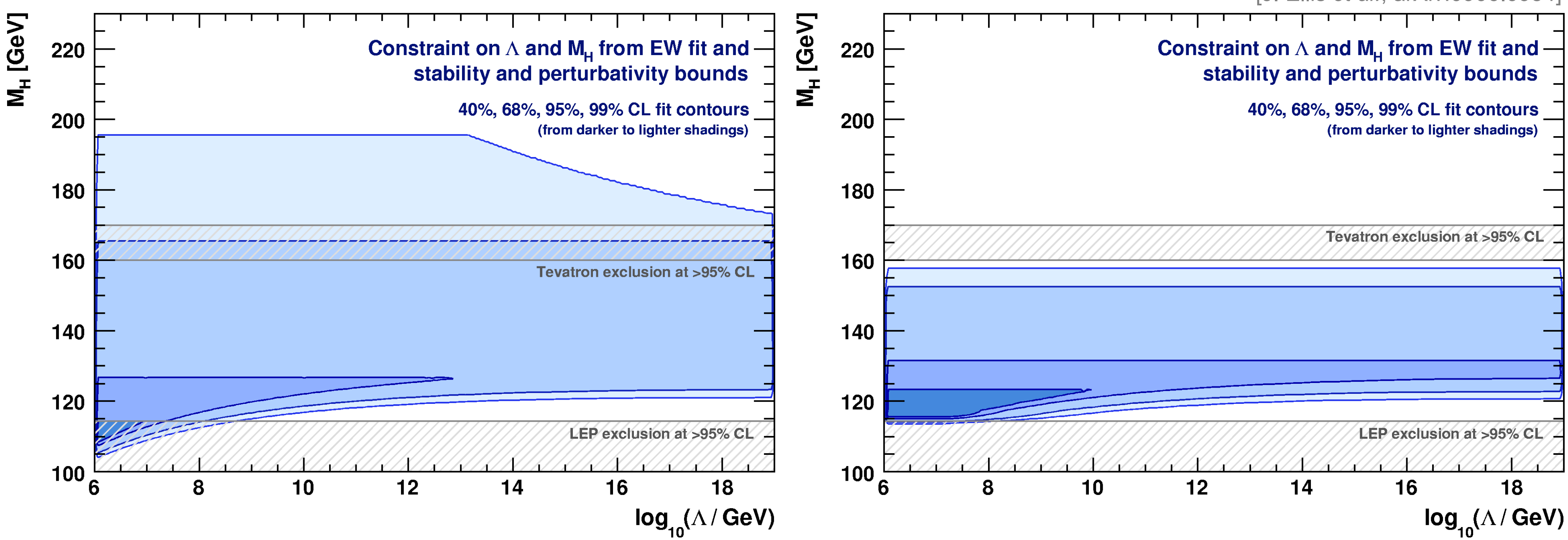


Convolve Bounds with M_H Constraints

Can we obtain likelihoods on vacuum stability (or, likewise, the cut-off = new physics scale Λ) from constraint on M_H ?

- Non-perturbativity excluded at 95.7% CL → raise to 99.1% with Tevatron Higgs searches !
- Cannot distinguish between vacuum stability, metastability or collapse scenarios
  → requires M_H > 122 GeV to exclude collapse scenario at 95% CL

[J. Ellis *et al.*, arXiv:0906.0954]

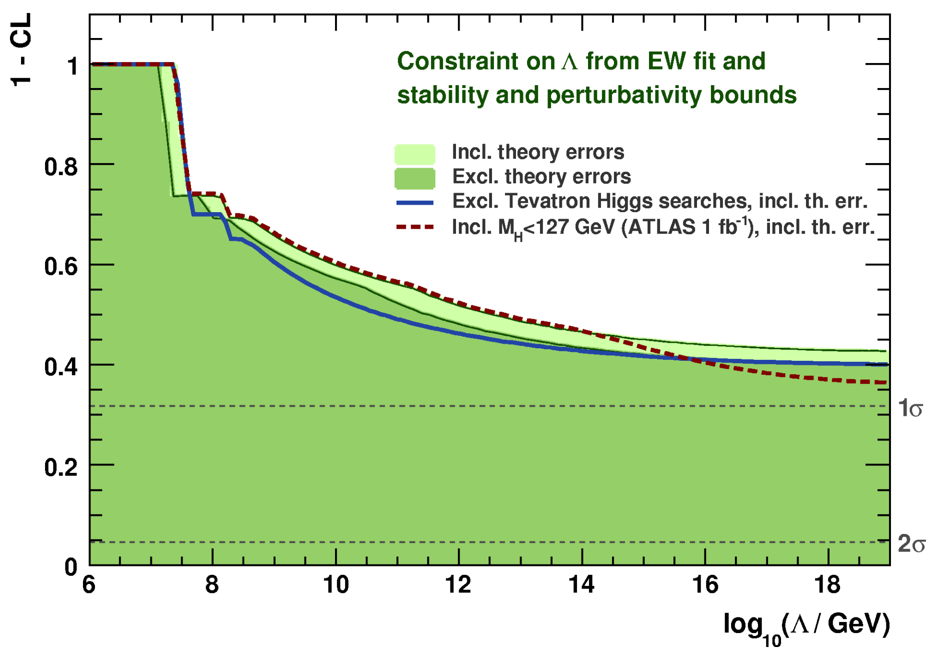


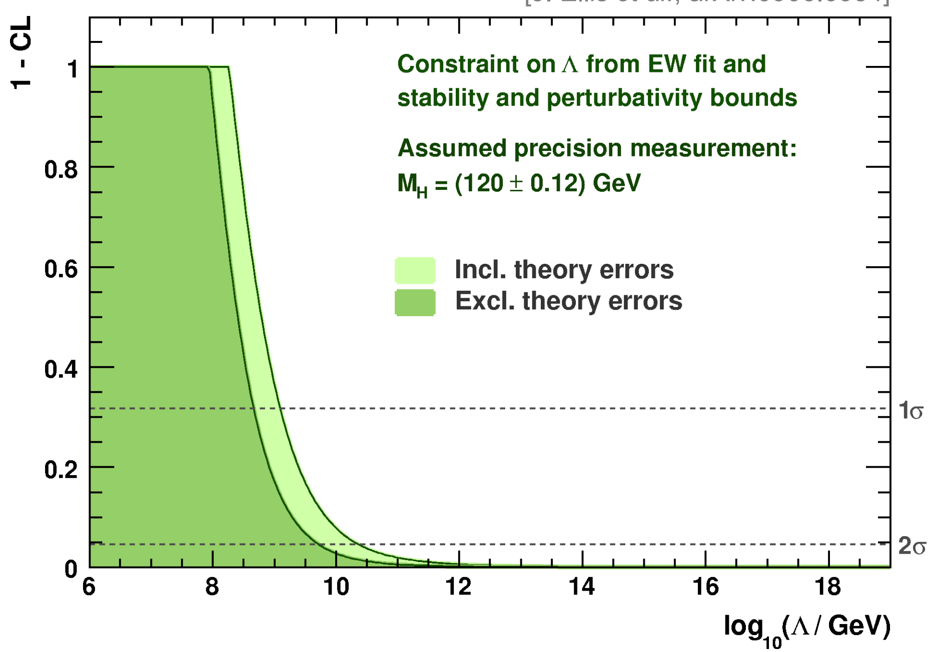
Convolve Bounds with M_H Constraints

Can we obtain likelihoods on vacuum stability (or, likewise, the cut-off = new physics scale Λ) from constraint on M_H ?

- Requiring absolute vacuum stability (at all times), one can obtain upper bound Λ
  - Left plot: current situation → no significant information
  - Right plot: case for precise M_H measurement of **120 GeV**

[J. Ellis *et al.*, arXiv:0906.0954]



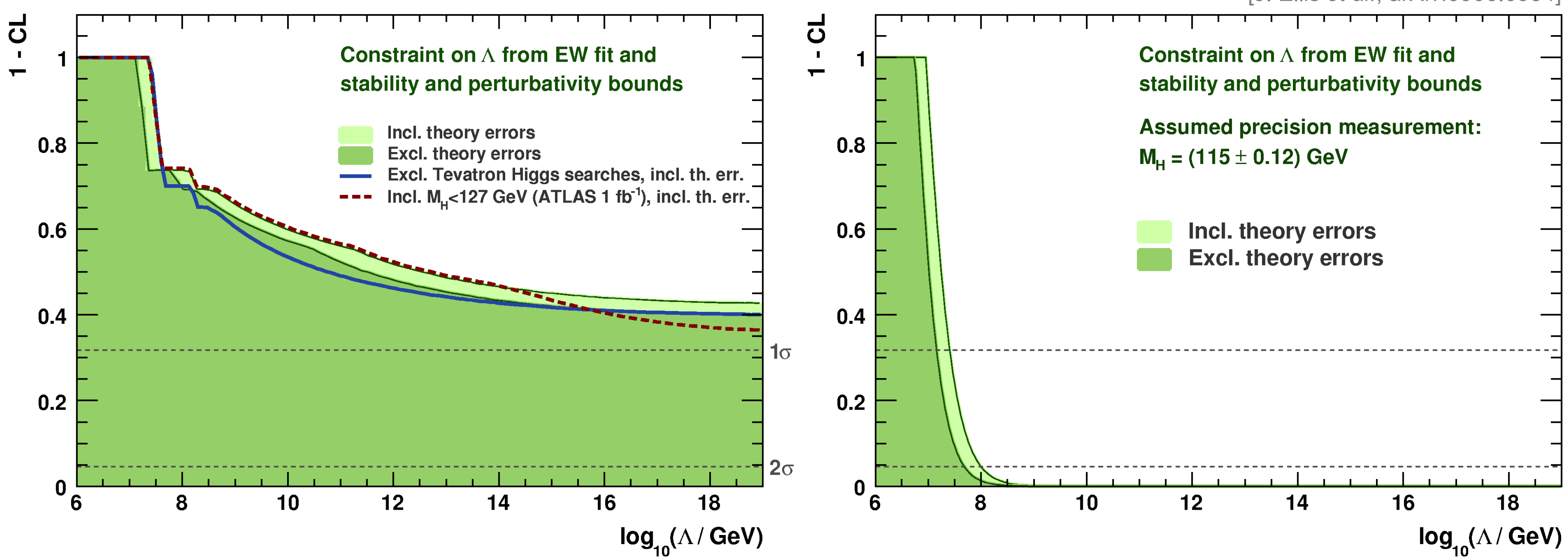


Convolve Bounds with M_H Constraints

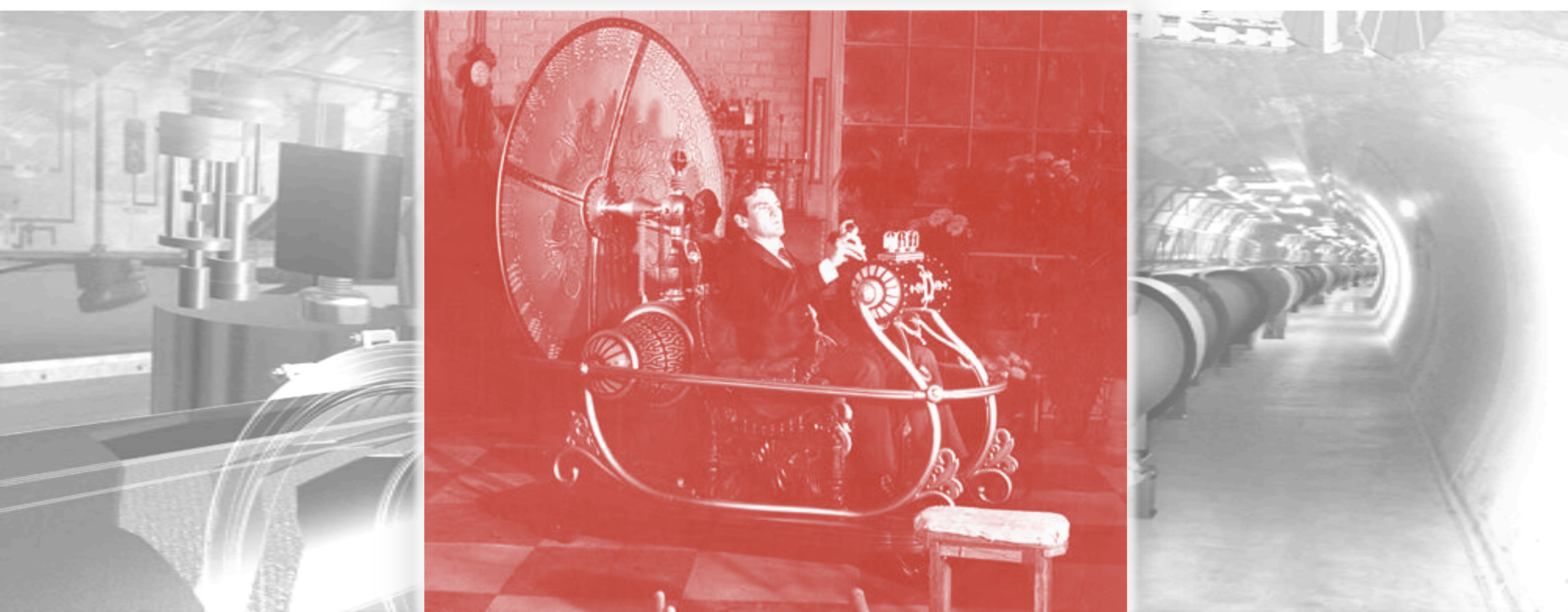
Can we obtain likelihoods on vacuum stability (or, likewise, the cut-off = new physics scale Λ) from constraint on M_H ?

- Requiring absolute vacuum stability (at all times), one can obtain upper bound Λ
  - Left plot: current situation → no significant information
  - Right plot: case for precise M_H measurement of **115 GeV**

[J. Ellis *et al.*, arXiv:0906.0954]



Prospects for the Standard Model 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*)
- δm_t: 1.2 GeV → 1.0 GeV

Expected improvement from ILC:

- From threshold scan δm_t = 50 MeV, translates to 100–200 MeV on the running mass

Expected improvement from GigaZ:

- From *WW* threshold scan: δM_W = 6 MeV
- From A_{LR}: $\delta \sin^2\theta^l_{\text{eff}}$: $17\cdot10^{-5}$ → $1.3\cdot10^{-5}$
- δR_l^0: $2.5\cdot10^{-2}$ → $0.4\cdot10^{-2}$

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

- Needs improvement in hadronic cross section data around *cc* res.
- Expected uncertainty of $7\cdot10^{-5}$ (today $22\cdot10^{-5}$) 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

Assumed experimental improvements for prospective study:

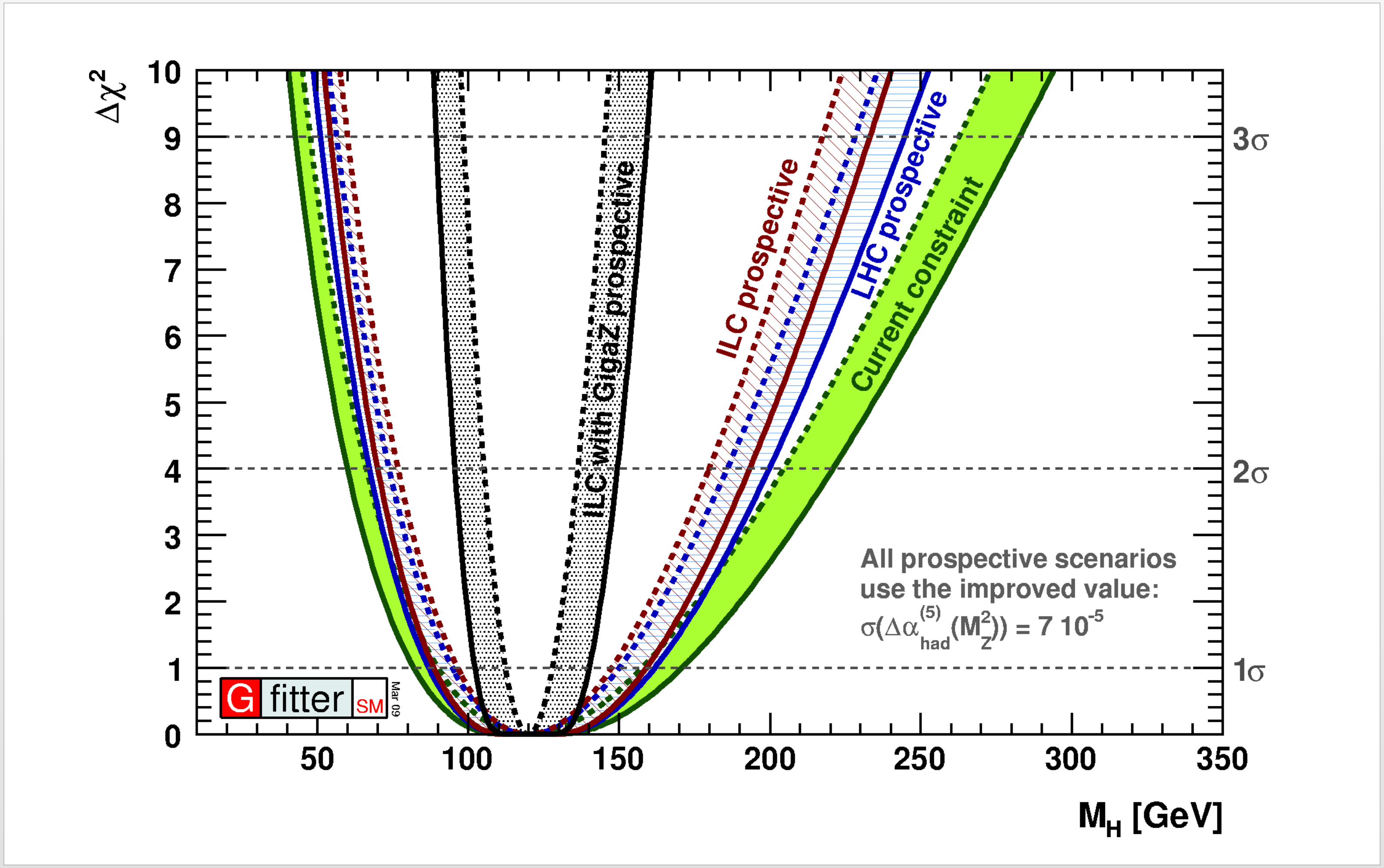
- LHC: M_W, m_{top}
- ILC: M_W, m_{top}
- Giga-Z: M_W, m_{top}, $\sin^2\theta^l_{eff}$, R_{lep}
- ISR-based (BABAR) and BESIII cross-section measurements should improve $\Delta\alpha^{had}(M_Z)$

Quantity	Expected uncertainty			
	Present	LHC	ILC	GigaZ (ILC)
M_W [MeV]	23	15	15	6
m_t [GeV]	1.3	1.0	0.2	0.1
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	17	17	17	1.3
R^0_ℓ $[10^{-2}]$	2.5	2.5	2.5	0.4
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $[10^{-5}]$	22 (7)	22 (7)	22 (7)	22 (7)
$M_H(= 120$ GeV) [GeV]	${}^{+54}_{-40}$ $({}^{+51}_{-38})$ $[{}^{+38}_{-30}]$	${}^{+45}_{-35}$ $({}^{+42}_{-33})$ $[{}^{+30}_{-25}]$	${}^{+42}_{-33}$ $({}^{+39}_{-31})$ $[{}^{+28}_{-23}]$	${}^{+26}_{-23}$ $({}^{+20}_{-18})$ $[{}^{+8}_{-8}]$
$\alpha_s(M_Z^2)$ $[10^{-4}]$	28	28	28	6

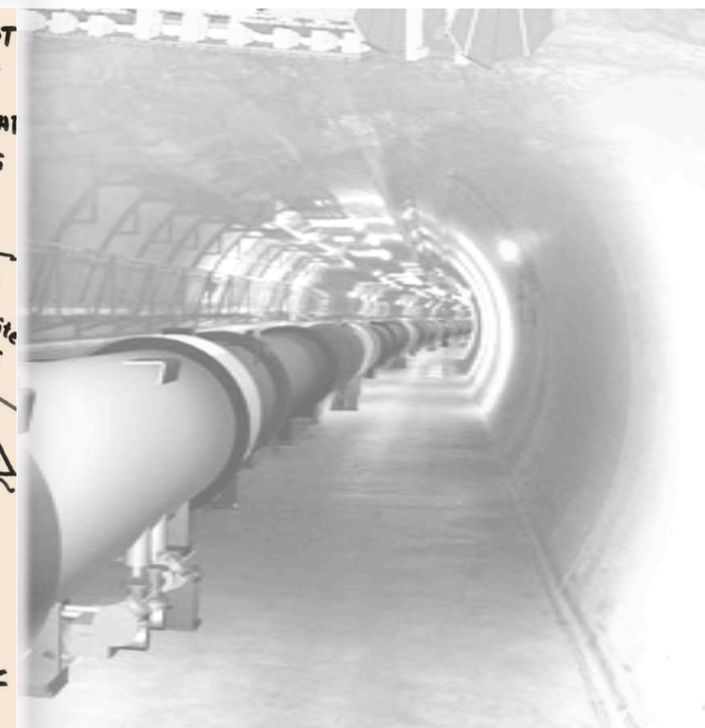
Input from: [ATLAS, Physics TDR (1999)] [CMS, Physics TDR (2006)] [A. Djouadi et al., arXiv:0709.1893][I. Borjanovic, EPJ C39S2, 63 (2005)] [S. Haywood et al., hep-ph/0003275] [R. Hawkings, K. Mönig, EPJ direct C1, 8 (1999)] [A. H. Hoang et al., EPJ direct C2, 1 (2000)] [M. Winter, LC-PHSM-2001-016]

Prospects for LHC, ILC and ILC with Giga-Z

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

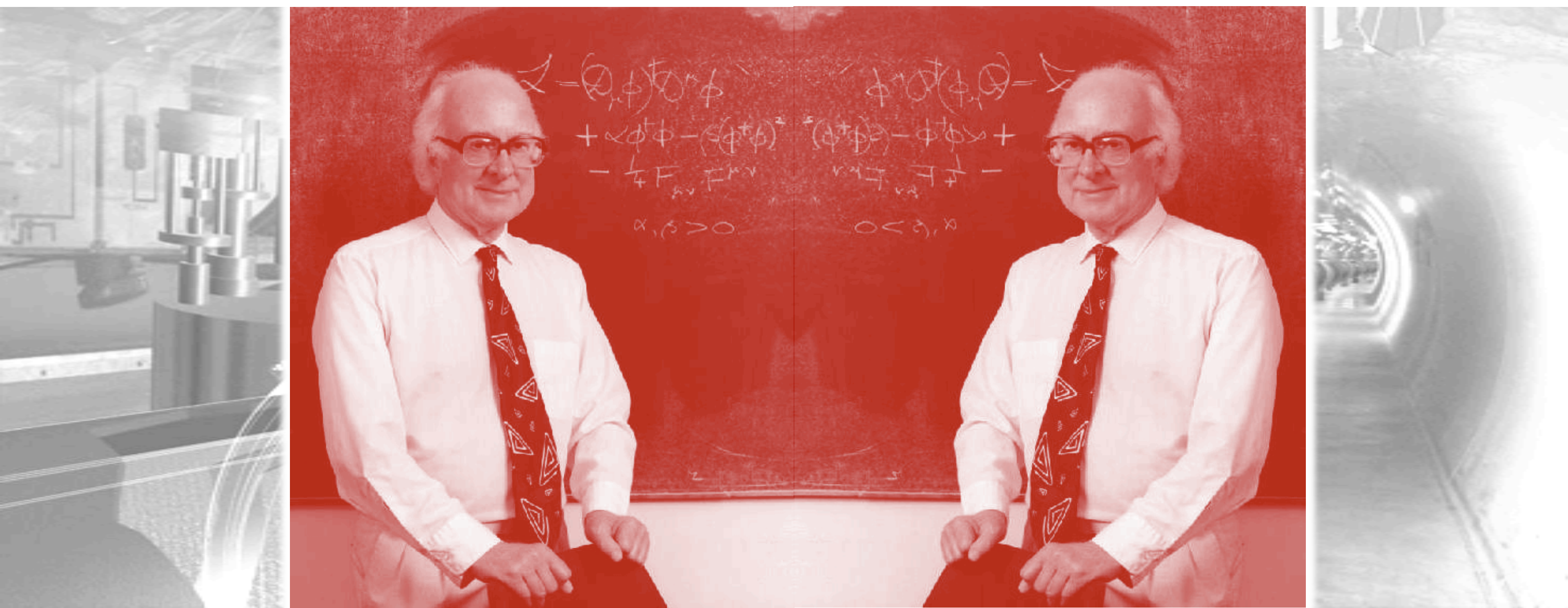


Probing New Physics with the EW Fit



G fitter

The Two-Higgs-Doublet Model (2HDM)



Two-Higgs-Doublet Model

Extend SM by adding another scalar Higgs doublet (2HDM)

- *Type-II* 2HDM: one doublet couples to up-type and the other one to down-type fermions only
- 6 free parameters: $\underline{M_h}$, M_{A0}, M_{H0}, $M_{H\pm}$, $\tan\beta = v_2 / v_1$, α (governing h–H^0 mixing)
- Resembles Higgs sector of MSSM

Look, *e.g.*, at processes sensitive to charged Higgs: $M_{H\pm}$

$$L_{H^\pm ff} = \frac{g}{2\sqrt{2}M_W}\left\{H^+\bar{U}\left[M_U V_{CKM}\left(1-\gamma_5\right)\cot\beta + V_{CKM}M_D\left(1+\gamma_5\right)\tan\beta\right]D + \text{h.c.}\right\}$$

- Interaction has similar structure as W boson
- Left-handed coupling: $1/\tan\beta$, right-handed coupling: $\tan\beta$
- Sensitive parameters are $M_{H\pm}$ and $\tan\beta$
- LEP limit: $M_{H\pm}$ > 78.6 GeV (95% CL), for any value of $\tan\beta$

Sensitive observables mostly from *B*-physics sector, but also *c* and *s*

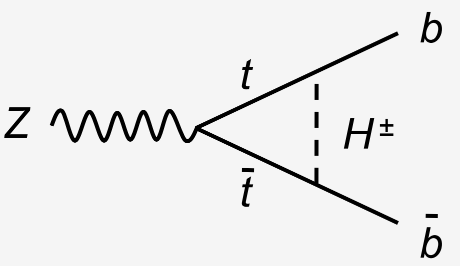
Two-Higgs-Doublet Model

Observables used to constrain charged Higgs in 2HDM

Observable	Input value	Exp. Ref.	Calculation
R_b^0	0.21629 ± 0.00066	[ADLO, Phys. Rept. 427, 257 (2006)]	[H. E. Haber and H. E. Logan, Phys. Rev. D62, 015011 (2000)]
BR $(B \to X_s\gamma)$	$(3.52 \pm 0.23 \pm 0.09)\cdot 10^{-4}$	[HFAG, latest update]	[M. Misiak et al., Phys. Rev. Lett. 98, 022002 (2007)]
BR $(B \to \tau\nu)$	$(1.73 \pm 0.33)\cdot 10^{-4}$	[P.Chang, Talk at ICHEP 2008]	[W. S. Hou, Phys. Rev. D48, 2342 (1993)]
BR $(B \to \mu\nu)$	$(-5.7\pm6.8\pm7.1)\cdot 10^{-4}$	[E. Baracchini, Talk at ICHEP 2008]	[W. S. Hou, Phys Rev. D48, 2342 (1993)]
BR $(K \to \mu\nu)$ / BR$(\pi \to \mu\nu)$	1.004 ± 0.007	[FlaviaNet,, arXiv: 0801.1817]	[FlaviaNet, arXiv: 0801.1817]
BR$(B \to D\tau\nu)$ / BR$(B \to De\nu)$	$0.416 \pm 0.117 \pm 0.052$	[Babar, Phys. Rev. Lett 100, 021801 (2008)]	[J. F. Kamenik and F. Mescia, arXiv: 0802.3790]

R_b^0 and $B \to X_s\gamma$

Z-vertex correction $\propto \cot^2\beta$

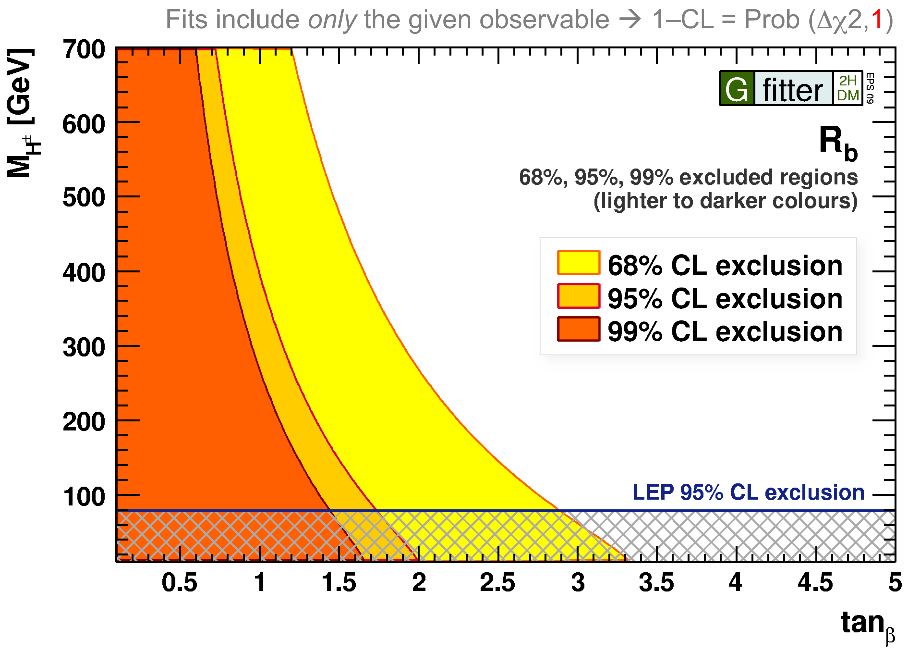


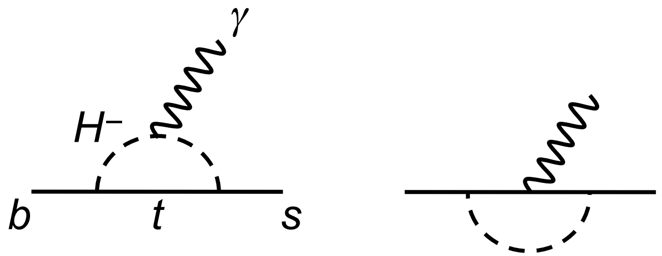
R_b^0 sensitive to small $\tan\beta$ only

Penguin dipole-moment of $B \to X_s\gamma$ allows combination of left- and right-handed Higgs couplings.

Wilson coefficient:

$$C_7^H \approx -\frac{m_t^2}{2M_H^2}\left(\frac{7}{36}\cot^2\beta + \frac{2}{3}\ln\frac{M_H^2}{m_t^2} - \frac{1}{2}\right)$$





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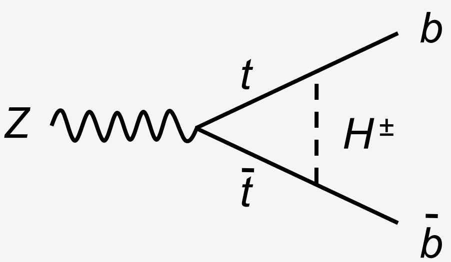

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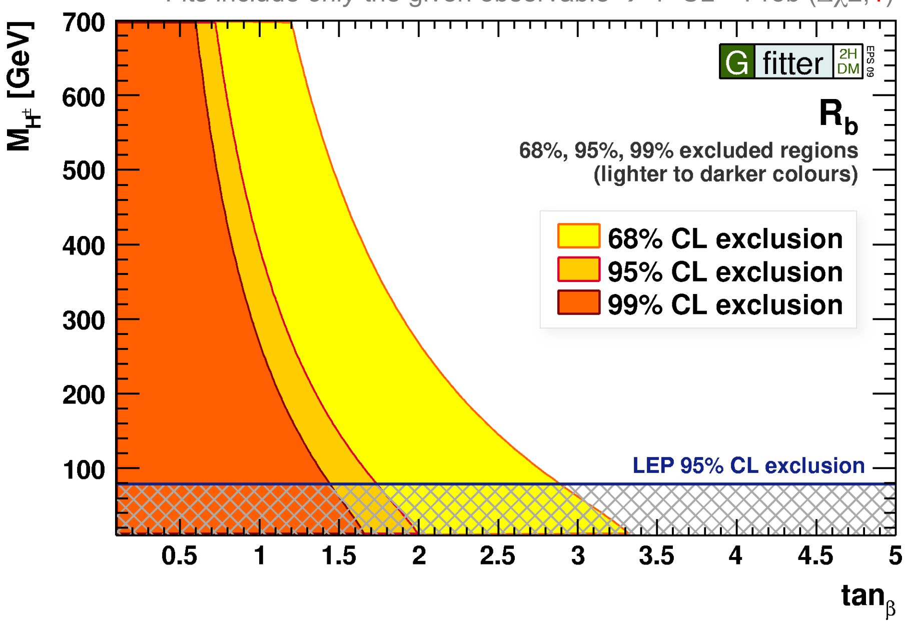
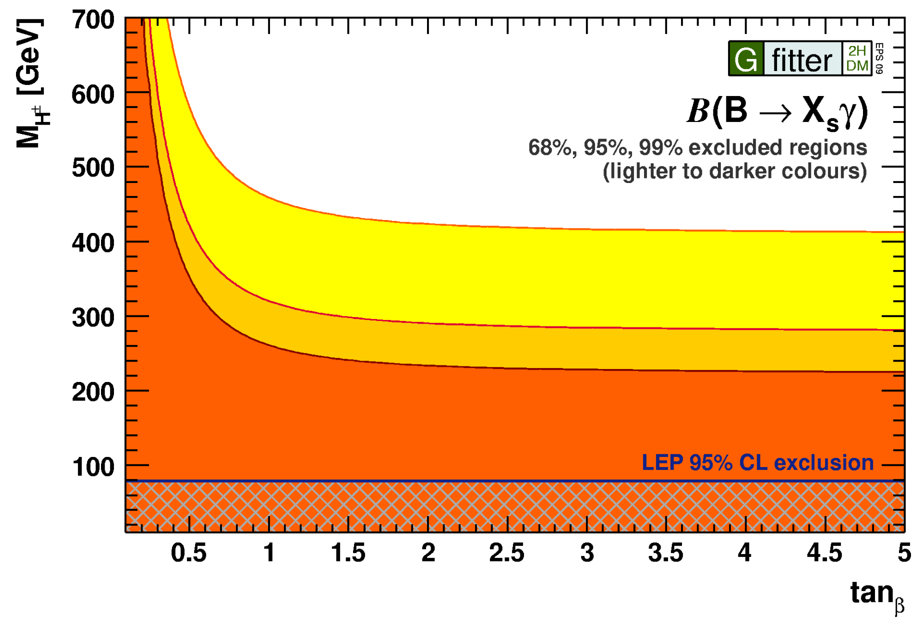
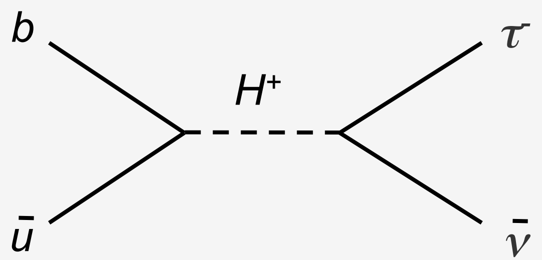
Fits include *only* the given observable → 1–CL = Prob (Δχ2,1)





$B \to \tau\nu$

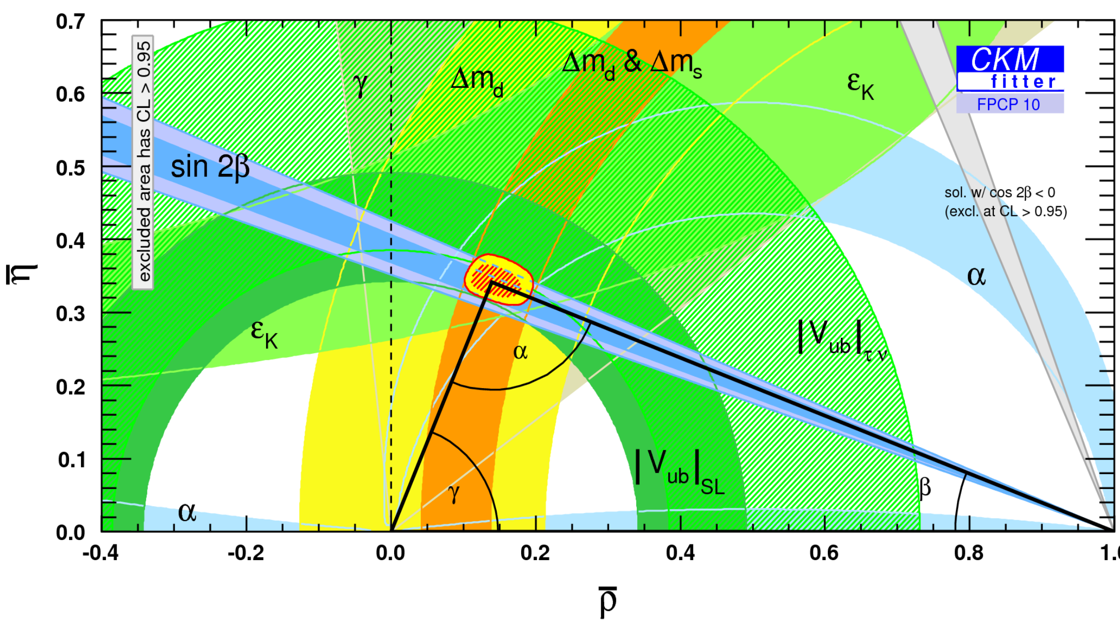


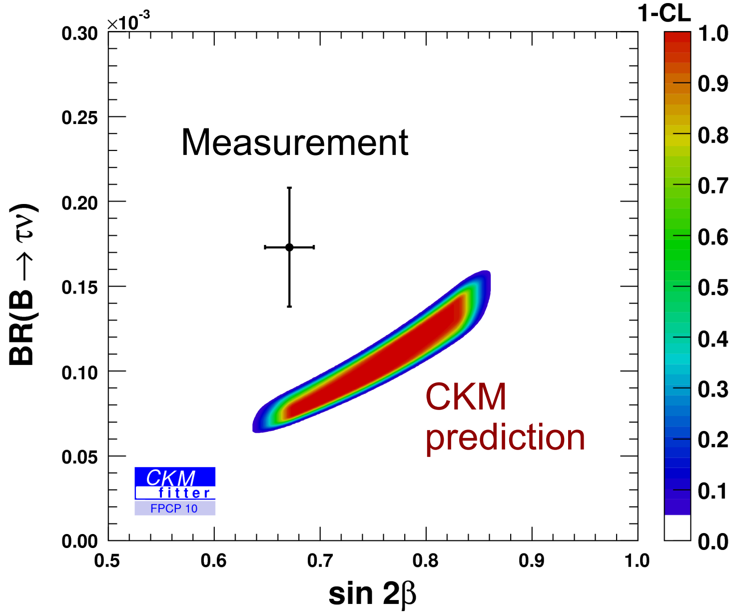
Weak annihilation process. BR proportional to $|V_{ub}|^2$ and B decay constant-squared f_B^2

$$\Gamma(B \to \tau\nu) = \frac{G_F}{8\pi} \cdot m_{B^+} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 \cdot f_B^2 \left|V_{ub}\right|^2 \cdot \left(1 - \frac{m_{B^+}^2}{M_{H^\pm}^2} \tan^2\beta\right)^2$$

Quadratic solution
Strength of effect $\propto \tan\beta$

Conflict (2.6σ) between direct BR measurement and SM prediction governed by CKM angle β





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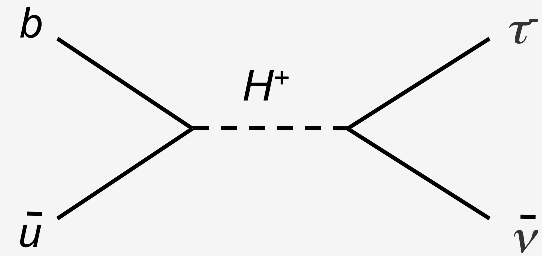

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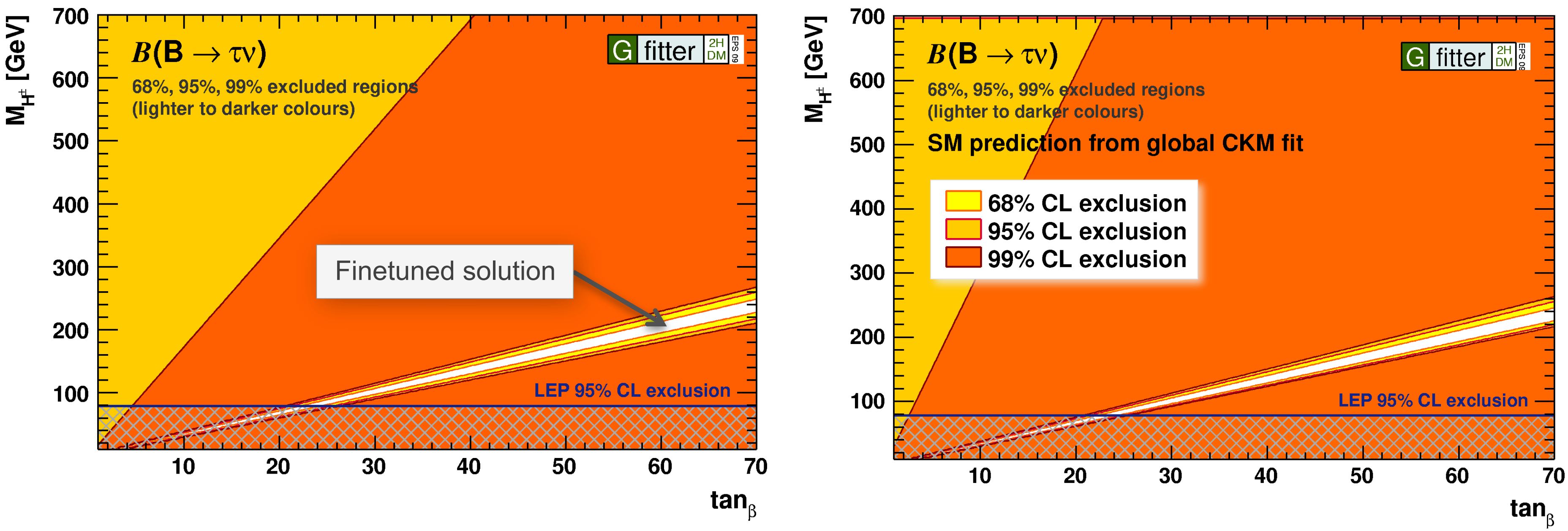
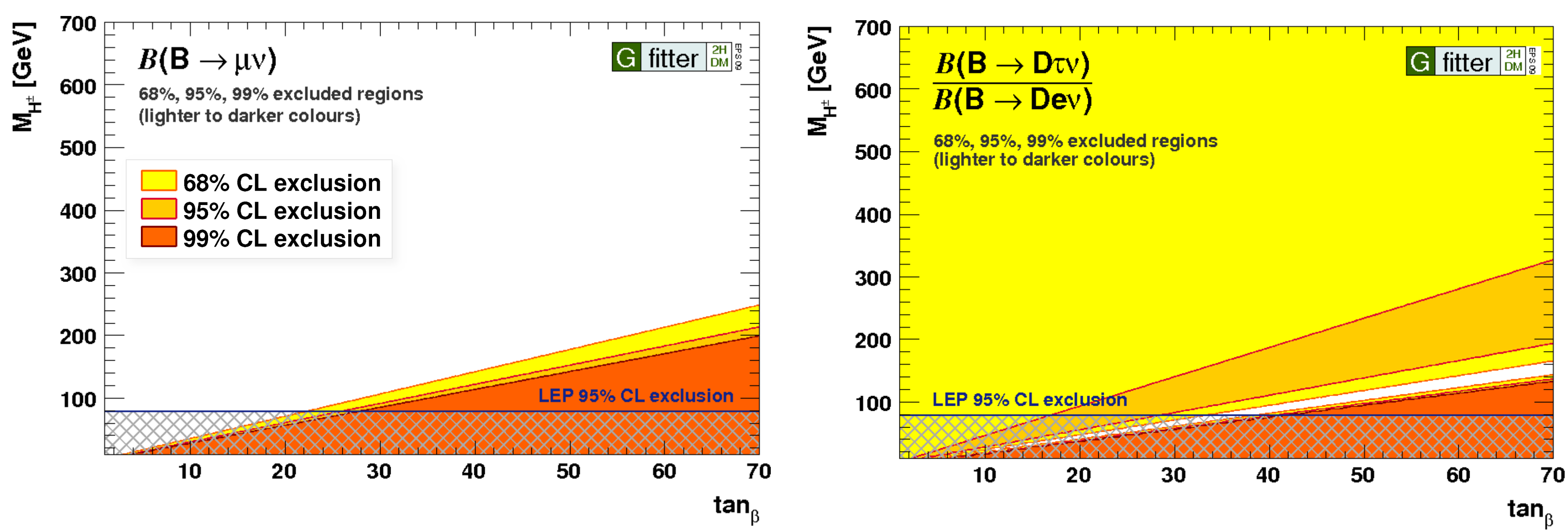
Quadratic solution
Strength of effect $\propto \tan\beta$

Compare BR predictions based on direct measurements of $|V_{ub}|$ (left) with CKM fit (right)



Other measurements with tree level contributions

- Weak upper limit on BR($B \to \mu\nu$)
- Favored solution of BR($B \to \tau\nu$) excluded by combination of:
  - BR($B \to X_s\gamma$)
  - BR($B \to D\tau\nu$) / BR($B \to De\nu$)
  - BR($K \to \mu\nu$) / BR($\pi \to \mu\nu$)



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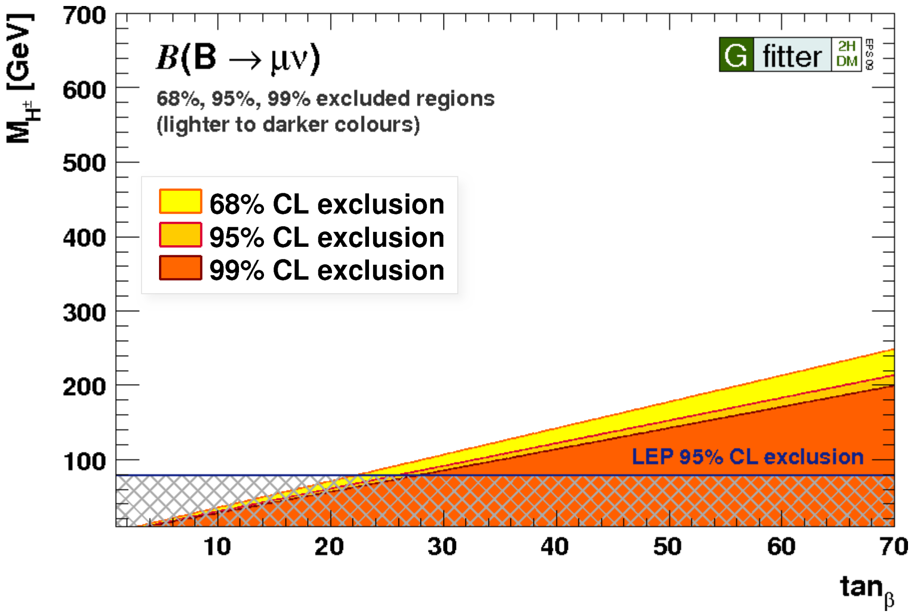
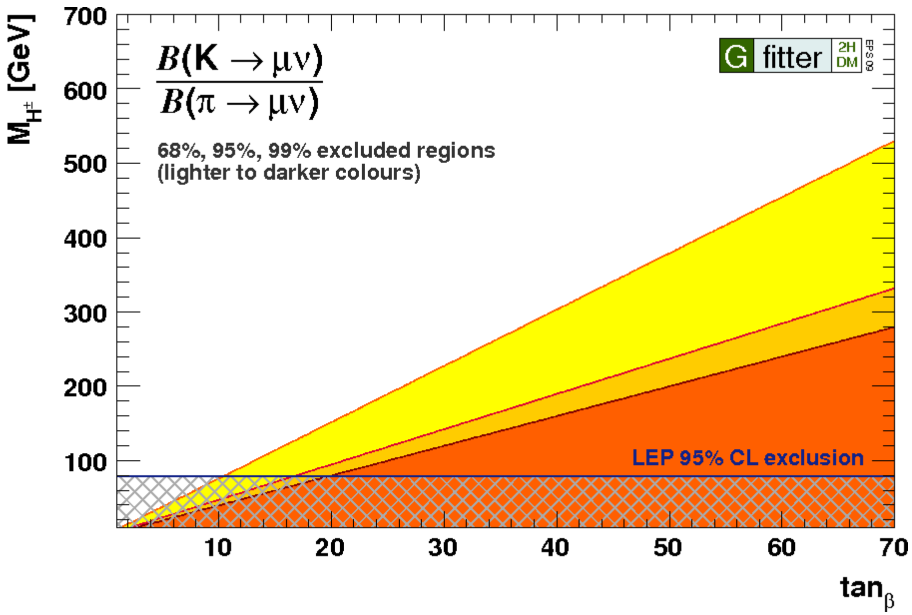


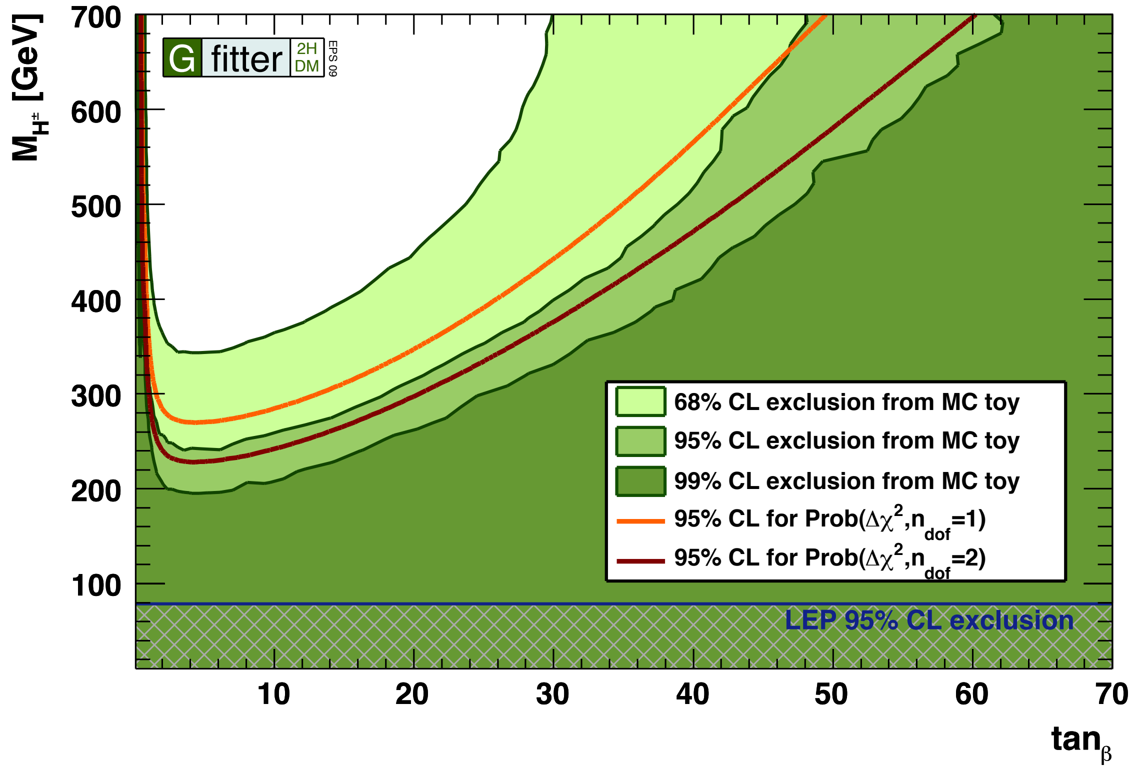


2HDM – Combined Fit

Fit minimum: $\chi^2 = 3.9$ for $M_{H\pm} = 858$ GeV and tan$\beta = 6.8$

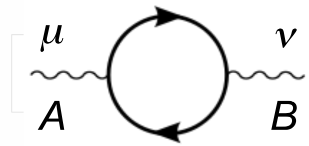
Excluded at 95% CL

- Small tanβ
- $M_H < 240$ GeV for all tanβ
- $M_H < 780$ GeV for tan$\beta = 70$ (mostly from $B \rightarrow \tau\nu$)



Oblique Corrections

Oblique = vacuum polarisation (VP) corrections –
Universal: occur in any gauge boson propagator



$= i\Pi^{\mu\nu}_{AB}(q)$

Assume that new (heavy) physics contributes to VP only

- Direct corrections (vertex, box, bremsstrahlung) generally suppressed by m_f / Λ
- Eminent exception: $\Gamma(Z \rightarrow bb)$, which has CKM-enhanced top vertex corrections

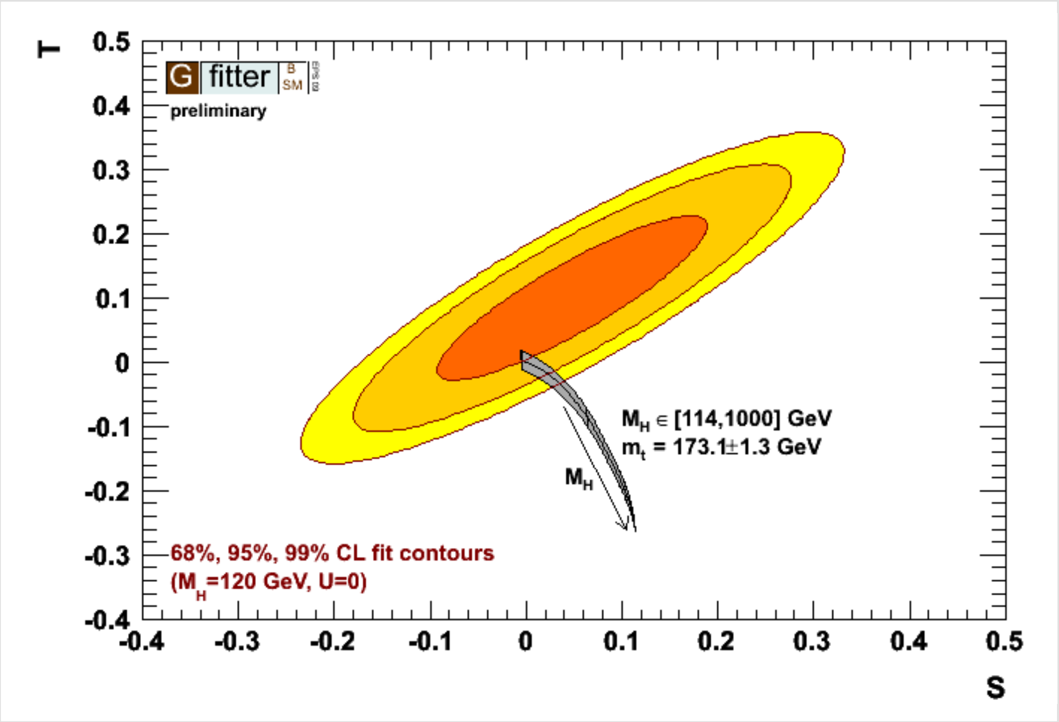
Electroweak fit is sensitive to the new physics via these oblique corrections parametrised with "STU" parameters (and more)

$$O_{\text{measured}} = O_{\text{SM, ref}}(M_H, m_t) + c_s S + c_t T + c_u U, \quad (S = T = U = 0 \text{ in SM})$$

STU measure deviations from EW radiative correction expected in $O_{\text{SM, ref}}$

- ***S***: new physics contribution to **neutral current processes**
- ***U*** (& *S*): new physics contribution to **charged current processes**
  - U only sensitive to M_W and Γ_W – usually very small in new physics models (often: U=0)
- ***T***: **difference** between neutral and charged current processes (sensitive to weak isospin violation)

Oblique Corrections



SM only:

- Ellipses are exp. errors on observables
- "Theory" is SM, with uncertainties in m_t and M_H

STU measure deviations from EW radiative correction expected in $O_{\mathrm{SM,\ ref}}$

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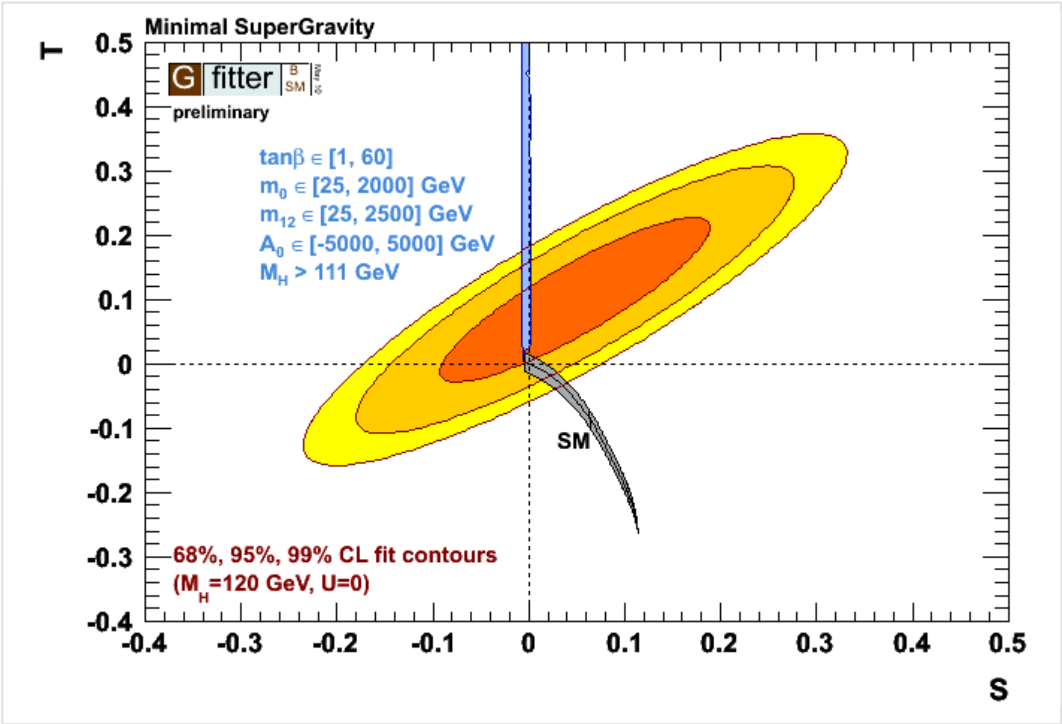
Oblique Corrections



mSUGRA:

- Prediction of STU dominated by weak isospin violation in stop and sbottom and between $stop_1$ and $stop_2$
- Only contributions to T
- Small variation in S from M_h allowed range

STU measure deviations from EW radiative correction expected in $O_{SM, ref}$

- ***S***: new physics contribution to **neutral current processes**
- ***U*** (& *S*): new physics contribution to **charged current processes**
  - U only sensitive to M_W and Γ_W – usually very small in new physics models (often: U=0)
- ***T***: **difference** between neutral and charged current processes (sensitive to weak isospin violation)


We’ve shaken enough !


Let’s open the box – finally !