Electroweak Physics: Results from Experiments and Interpretations, Complementarity with future LHC Results, Precisions to be reached

(Experiment)

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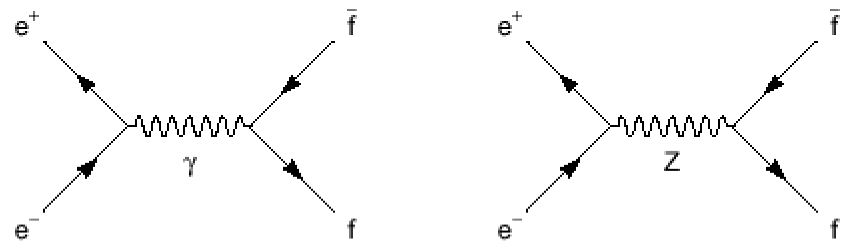
Outline

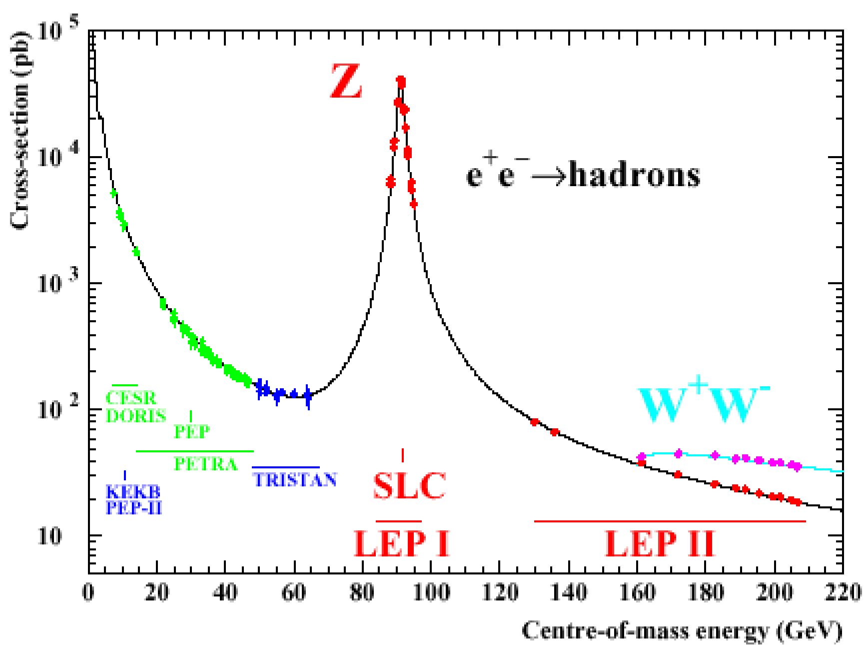
- Reminders of the standard model
- LEP & SLC precision neutral current electroweak data
- LEP & Tevatron Electroweak Data
- Electroweak Expectations from LHC
- Summary

Z-fermion Couplings

$$\mathrm{L}_{\mathrm{EW}} = \mathrm{L}_{\mathrm{Z}} + \mathrm{L}_{\mathrm{W}} + \mathrm{L}_{\gamma} + \mathrm{L}_{\mathrm{Higgs}} + \ldots$$

$$\mathrm{L}_{\mathrm{Z}} \sim \frac{e}{2\sin\theta_{\mathrm{W}}\cos\theta_{\mathrm{W}}}\bar{\psi}_f\left(g_{\mathrm{V}}^{\mathrm{f}}\gamma^{\mu} - g_{\mathrm{A}}^{\mathrm{f}}\gamma^{\mu}\gamma^{5}\right)\psi_f Z_{\mu}$$





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standard model Parameters

- 12 fermion masses; mixing matrix parameters (4 quark; 4 lepton), strong phase, and the following 5 precision parameters

Parameter	Measured Value	Experimental Method
α_s	0.1185 ± 0.0020	Tau Decays Deep Inelastic Scattering Z^0 Width Various Hadronic Measurements
α_{QED}	$0.7297352533 \times 10^{-2} \pm 0.27 \times 10^{-10}$	Quantum Hall Effect
G_F	$(0.116629 \pm 0.000001) \times 10^{-4} \mathrm{GeV}^{-2}$	Muon Decay
$\sin^2\theta_W^{\text{lep. eff.}}$	0.23135 ± 0.00014	neutrino scattering, Z^0 asymmetries **Møller**, **APV**
m_H	$> 113.5\,\mathrm{GeV}$ (95% CL) $88^{+53}_{-35}\,\mathrm{GeV}$	LEP Direct Search Electroweak Fit

note on “derived parameters”

- experimentalists view: choose the most precisely determined independent parameters to ‘define’ the standard model
- derive other standard model parameters:

$$\sin^2\theta_W = \frac{1}{2}\left(1-\sqrt{1-4\frac{\pi\alpha_{QED}}{\sqrt{2}G_F m_Z^2}}\right)$$

$$m_W = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\pi\alpha_{QED}}{\sqrt{2}G_F m_Z^2}}\right)$$

$$\alpha_{QED} \to \alpha_{QED}/(1-\Delta r)$$

Δr radiative corrections

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In particular choice of renormalization scheme the form of the SM relation:

$$\cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha(0)}{\sqrt{2}m_Z^2 G_F}\frac{1}{1-\Delta r}$$

is preserved:

$$\cos^2\theta_{eff}^f \sin^2\theta_{eff}^f = \frac{\pi\alpha(0)}{\sqrt{2}m_Z^2 G_F}\frac{1}{1-\Delta r^f}$$

$$\Delta r = \Delta\alpha + \Delta r_w$$

$$\Delta r^f = \Delta\alpha + \Delta r_W^f$$

$$\Delta\alpha(s) = \Delta\alpha_{e\mu\tau}(s) + \Delta\alpha_{top}(s) + \Delta\alpha_{had}^{(5)}(s)$$

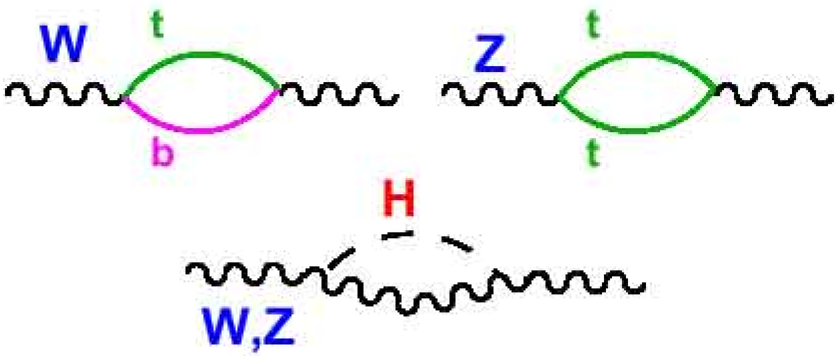
$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)}$$

$$\Delta r_W^f = -\Delta\rho + \ldots$$

$$\Delta r_w = -\frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + \ldots$$

Radiative corrections give sensitivity of precision measurements to the top and Higgs mass

- $\alpha_{\rm em}$, known to 45 ppb
  (but only to 200 ppm at $Q^2 \sim M_Z^2$)
- G_F, known to 10 ppm
- M_Z, known to 23 ppm



- Radiative corrections large, well-understood

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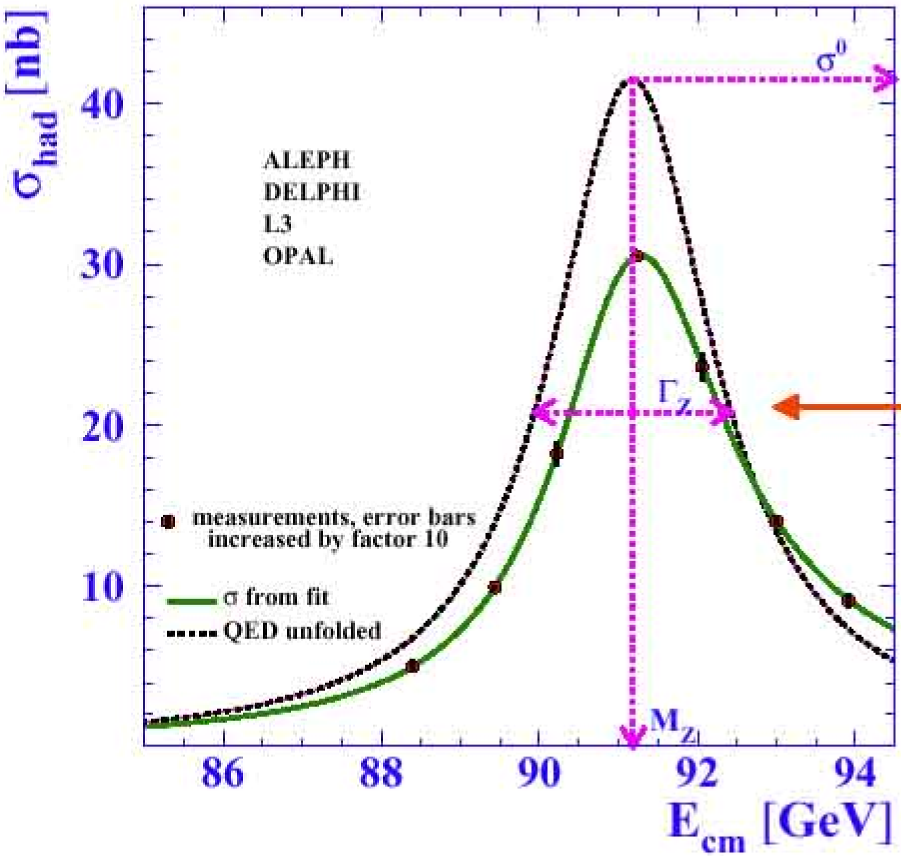
Z-lineshape: M_Z and Γ_Z



The 4 exps. collected 15.5 million Z decays to quarks plus 1.7 million decays to charged leptons, integrated L ≅ 200 pb^{-1} per exp.

The final hadronic cross section, measured and QED deconvoluted.

Radiative corrections large but v. well known.

The final result

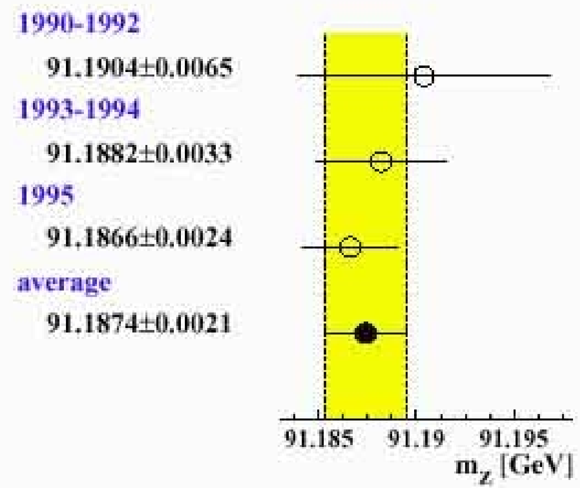
$2{\cdot}10^{-5}$ accuracy for one of the most fundamental constants:

$$m_Z = 91.1874 \pm \mathbf{0.0021}\ \text{GeV}$$

This cannot be exceeded with any one of the future machines, not even with a GigaZ Linear Collider!

Essential:

- Beam energy measurement using the technique of **resonant depolarisation** plus careful control of all machine parameters, still **dominant error of ±1.7 MeV,**
- Close cooperation with theory.



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Neutral Current Asymmetry Parameters

$$A_\ell = \frac{g_{L\ell}^2 - g_{R\ell}^2}{g_{L\ell}^2 + g_{R\ell}^2} = \frac{2 g_{V\ell} g_{A\ell}}{g_{V\ell} + g_{A\ell}}$$

$$= \frac{2\left(g_{V\ell} / g_{A\ell}\right)}{1 + \left(g_{V\ell} / g_{A\ell}\right)^2}$$

- $\left(g_{V\ell} / g_{A\ell}\right) = 1 - 4 \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

Z-fermion Couplings

- Neutral current parity violating observables are sensitive to $\sin^2\theta_W$: asymmetries give g_V/g_A
  - Left-right asymmetries at SLD: A_{LR}
  - Forward-backward asymmetries at LEP: A_{FB}
  - Tau polarisation measurement at LEP

- g_A is measured from cross sections: R_l
- Major focus of LEP and SLD on this sector of the standard model
- APV
- Møller Scattering

SLAC Linear Collider (SLC)
e+e- Collider with one experiment: SLAC Linear Detector (SLD)
Centre-of-mass at Z-pole 1992-1998

- electrons were longitudinally polarised
- 300k left-handed & 240k right-handed
- polarisation precisely measured
- 73%-77% for most of the data set
- Primary measure:

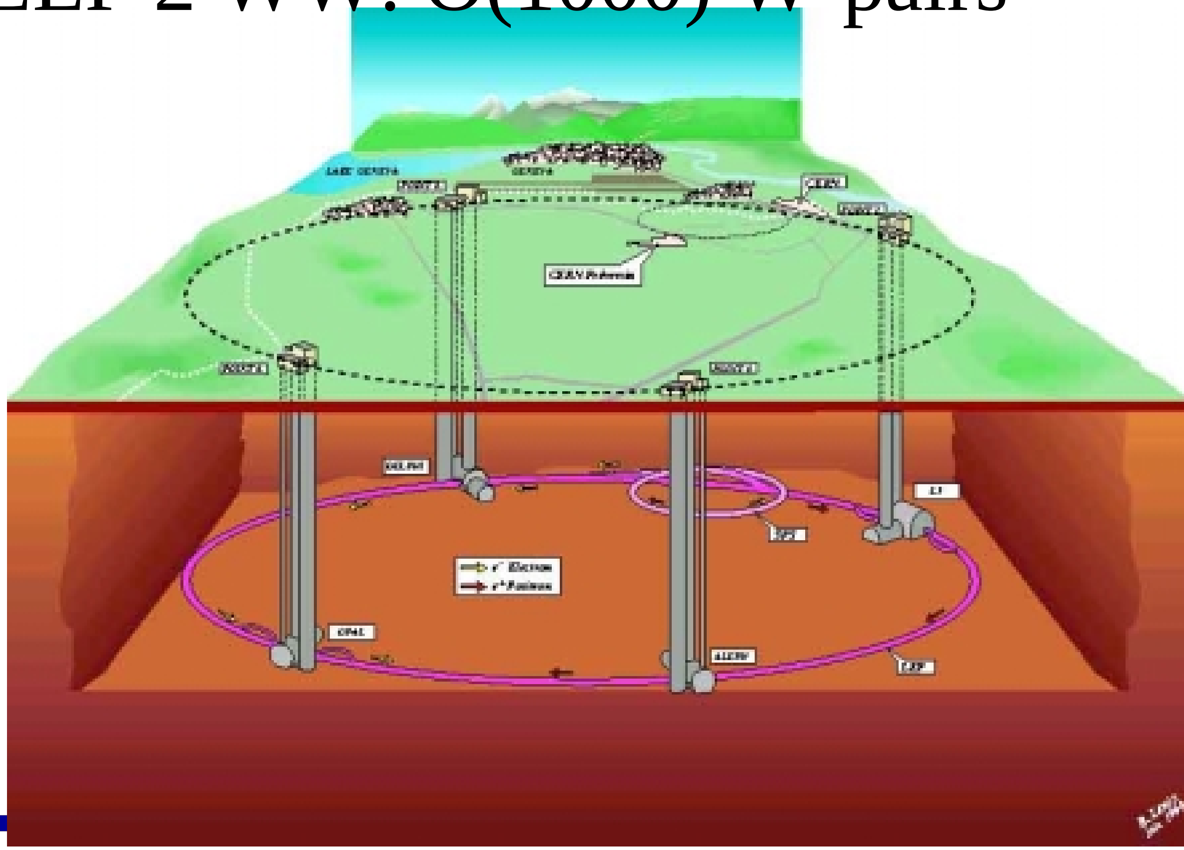
$A_{LR} = (N_L - N_R) / (N_L + N_R) \times (1/\langle Polarisation \rangle)$

$= \mathcal{A}_e = 0.1513 \pm 0.0021$

LEP 27km circumference e+e- synchrotron storage ring collider

1989-95 LEP 1 Z-pole: 3.5M Z decays per exp't

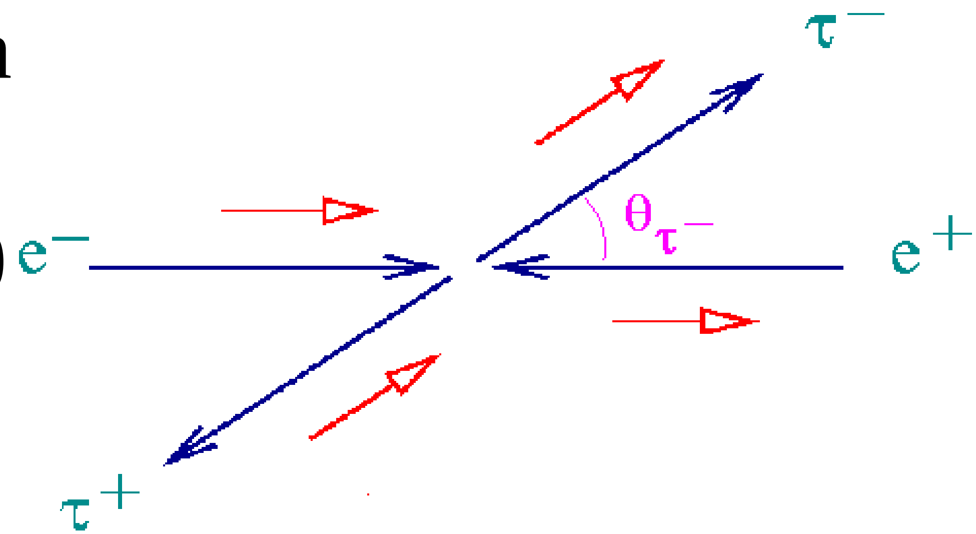
1995-00 LEP 2 WW: O(1000) W-pairs



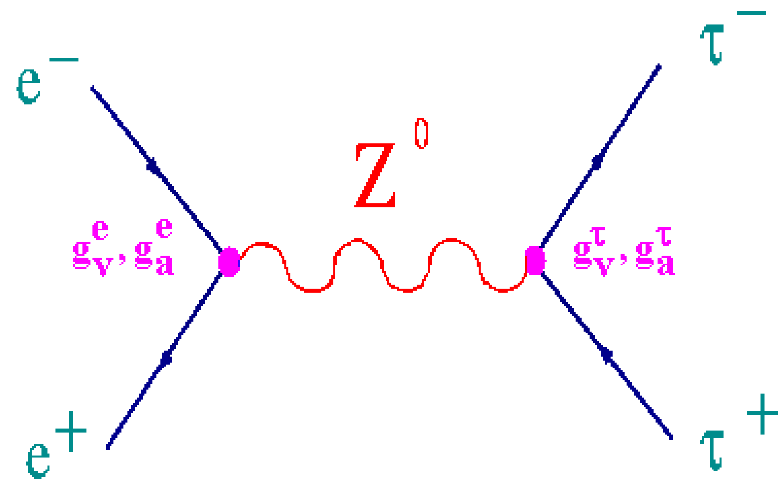
Z couples to all fermions

e.g. tau-pair production

$A_{FB} = (N_F - N_B)/(N_F + N_B)$



tree-level diagram:



Observables sensitive to couplings at LEP

The full set

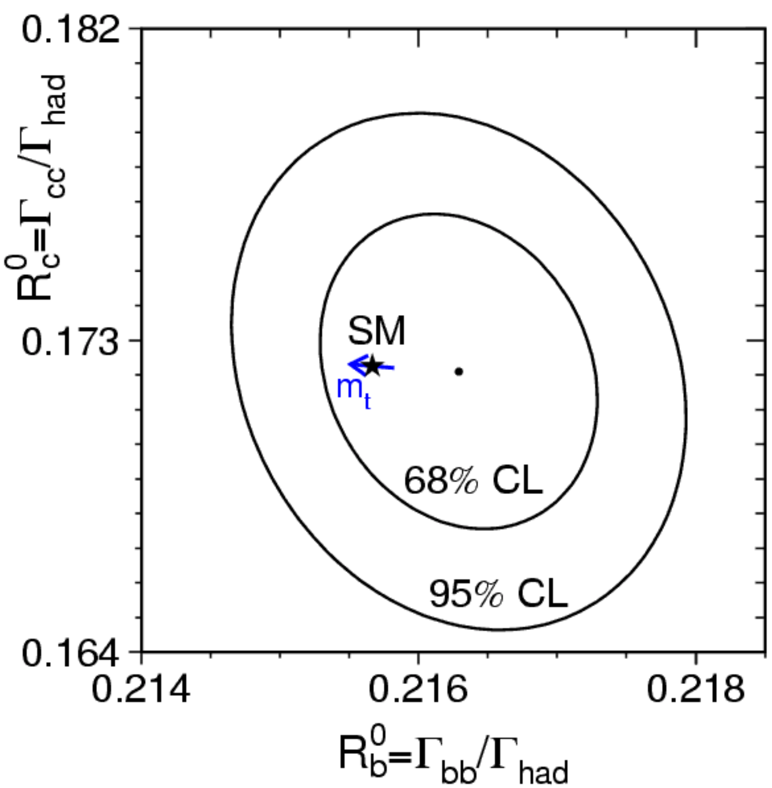
of nearly uncorrelated pseudo-observables from EWWG.

- Total Z width: $\Gamma_Z = 2.4952 \pm 0.0023$ GeV,
- Z peak cross section: $\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2} \cdot \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$,
- Ratios $R_f^0 \equiv \Gamma_{had}/\Gamma_{ff}$ for f = e,μ,τ; also $R_q^0 \equiv \Gamma_{qq}/\Gamma_{had}$ for q = b,c,s,
- Forward backward asymmetries for f = e,μ,τ; b,c,s. At Z pole:

$$A_{FB}^{0,f} \equiv \frac{3}{4} A_e A_f \qquad A_f \equiv \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2},$$

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

$Z \to q\bar{q}(g)$ (hadrons)



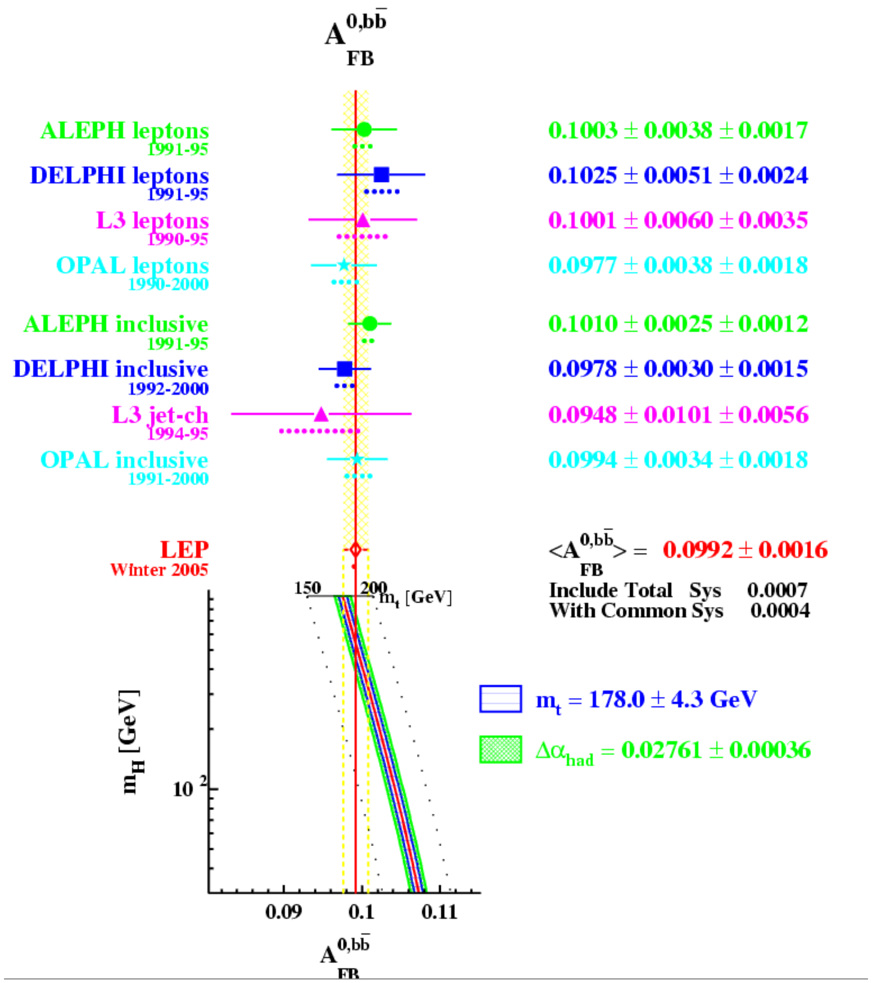
R_b agrees with SM!

$$R_b^0 \equiv \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} \qquad R_c^0 \equiv \frac{\Gamma_{c\bar{c}}}{\Gamma_{had}}$$

R_b contains higher order ew. contributions ~ m_t^2, nearly independent of QCD, QED or other ew. corr.

Measurement of R_b requires extremely high quality of b tagging.
→ High resolution silicon microvertex detectors + multi-tag methods + control of hemisphere correlations …

$Z \to b\bar{b}$



All LEP measurements are consistent

$$A_b(\text{LEP only}) = \frac{4}{3}\frac{A_{FB}^{0,b}}{A_\ell} = 0.881 \pm 0.017$$

$$A_b(\text{SLD}) = 0.923 \pm 0.020$$

Agree at 1.6σ

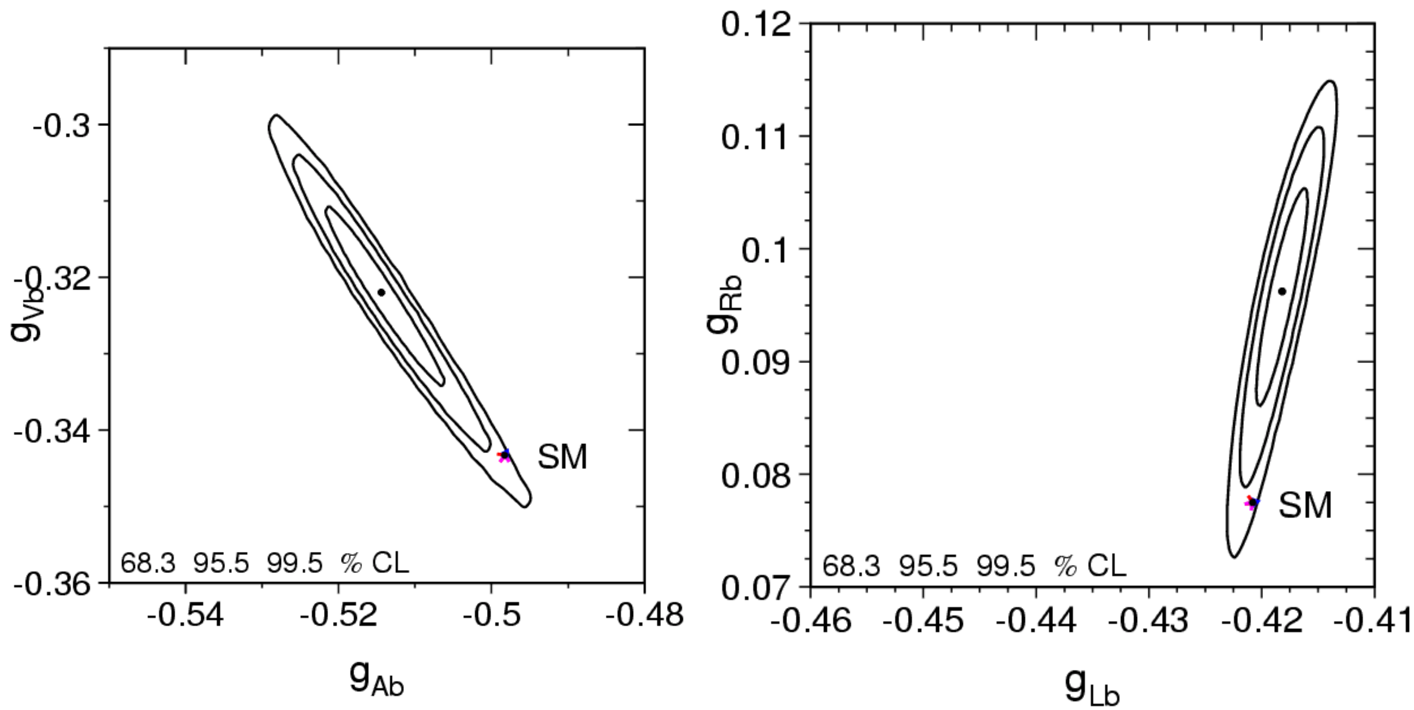
$$A_b(\text{LEP+SLD}) = 0.889 \pm 0.013$$

$$(0.935 \pm 0.001 \text{ SM}) 3.5\sigma$$

$Z \to b\bar{b}$

g_{Vb} versus g_{Ab}, g_{Rb} versus g_{Lb}

From R_b, $\mathcal{A}_b$, and A_{FB}^b, assuming lepton universality.



Strong anti-correlation of g_{Vb}, g_{Ab} due to constraint on sum of squares from precise R_b. Deviation from SM mainly for g_{Rb}.

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$Z \to b\bar{b}$

Can we trust $A^{0,b}_{FB}$?

Breakdown of errors for the **combined LEP** result:

- Statistics: $\Delta A^{0,b}_{FB}$ = **0.00156**
- Systematic:

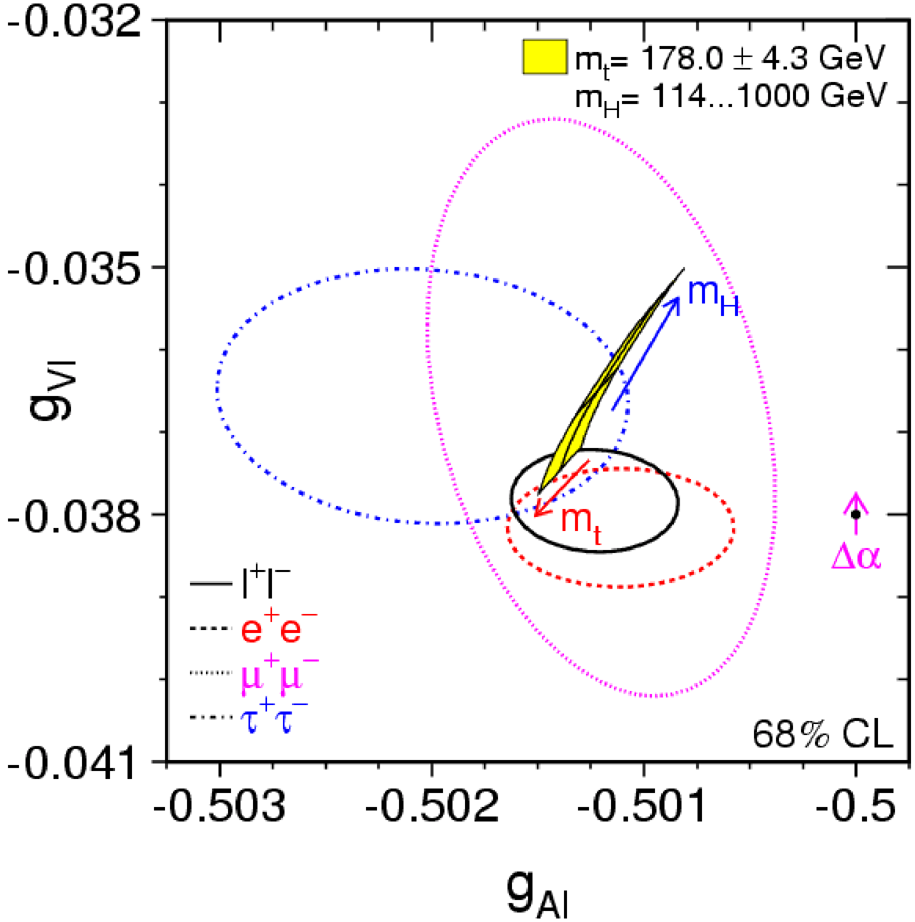
Uncorrelated	0.00061
Correlated	0.00039
Total systematic	0.00073

Small **correlated uncertainty**. Main contributions to correlated syst. uncertainty from physics:

- QCD correction (0.00030),
- Light quark fragmentation (0.00013),
- Semileptonic model $b \to l$ decays (0.00009),
- Gluon splitting $g \to b\bar{b}$ (0.00007), etc.

Conclusion: No reason to consider the $A^{0,b}_{FB}$ results as unreliable.

$Z \rightarrow e^+e^-; \mu^+\mu^-; \tau^+\tau^-$



Contributions from LEP:

- A_{FB} at Z pole,
- Partial widths $\Gamma_{ff} \sim g_{Vf}^2 + g_{Af}^2$,
- Longitudinal τ polarisation: A_τ, A_e.

Contributions from SLD:

- Asymmetry for left and right handed e^- polarisation: most precise A_e,
- A_{FB}^{LR}: A_e, A_μ, A_τ.

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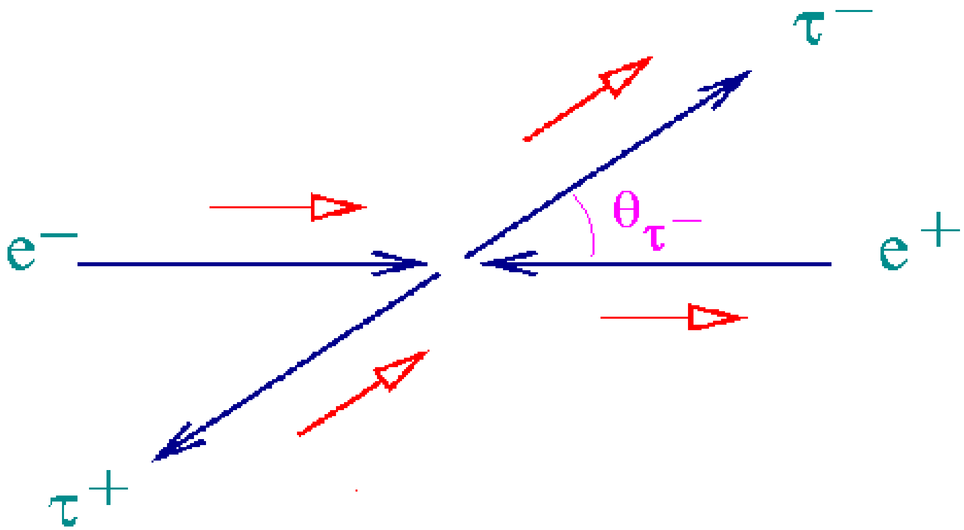
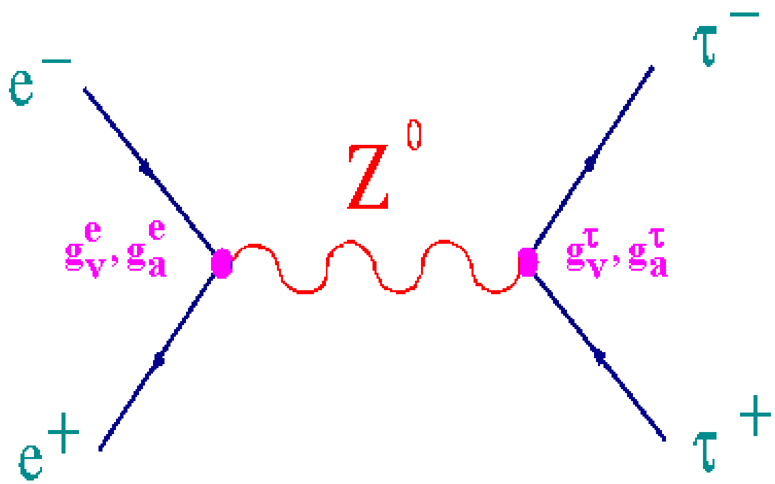
Tau Polarisation: $e^+e^- \to \tau^+\tau^-$ Production



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

- $\left(g_{V\ell}/g_{A\ell}\right) = 1 - 4\sin^2\theta_{\text{eff}}^{\text{lept}}$

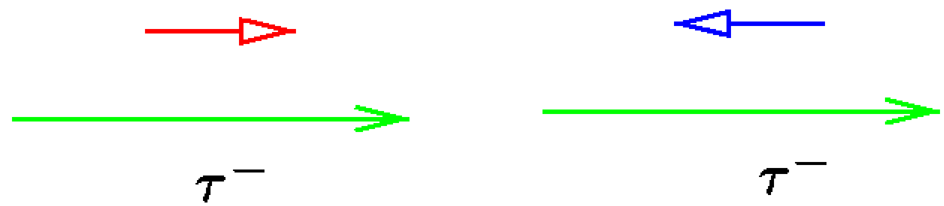


- Lepton universality: A_e and A_τ

Measure the Polarization

$$P_\tau = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\sigma_+ - \sigma_-}{\sigma_{\text{total}}}$$

+ helicity ~ right-handed **- helicity ~ left-handed**



$$P_\tau \equiv P_{\tau^-} = -P_{\tau^+}$$

$$\frac{1}{\sigma_{\text{total}}}\frac{d\sigma_+}{d\cos\theta_{\tau^-}} = \frac{3}{16}\left[\left(1+\langle P_\tau\rangle\right)\left(1+\cos^2\theta_{\tau^-}\right) + \frac{8}{3}\left(A_{FB} + A_{pol}^{FB}\right)\cos\theta_{\tau^-}\right]$$

$$\frac{1}{\sigma_{\text{total}}}\frac{d\sigma_-}{d\cos\theta_{\tau^-}} = \frac{3}{16}\left[\left(1-\langle P_\tau\rangle\right)\left(1+\cos^2\theta_{\tau^-}\right) + \frac{8}{3}\left(A_{FB} - A_{pol}^{FB}\right)\cos\theta_{\tau^-}\right]$$

$$\langle P_\tau \rangle = \frac{\sigma_+ - \sigma_-}{\sigma_{\text{total}}}$$ averaged over $\cos\theta_{\tau^-}$

$$A_{pol}^{FB} = \frac{\left[\sigma_+ - \sigma_-\right]_{\cos\theta_{\tau^-}>0} - \left[\sigma_+ - \sigma_-\right]_{\cos\theta_{\tau^-}<0}}{\sigma_{\text{total}}} \qquad A_{FB} = \frac{\left[\sigma\right]_{\cos\theta_{\tau^-}>0} - \left[\sigma\right]_{\cos\theta_{\tau^-}<0}}{\sigma_{\text{total}}}$$

$$\langle P_\tau \rangle = -\mathcal{A}_\tau \qquad A_{pol}^{FB} = -\frac{3}{4}\mathcal{A}_e \qquad A_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_\tau$$

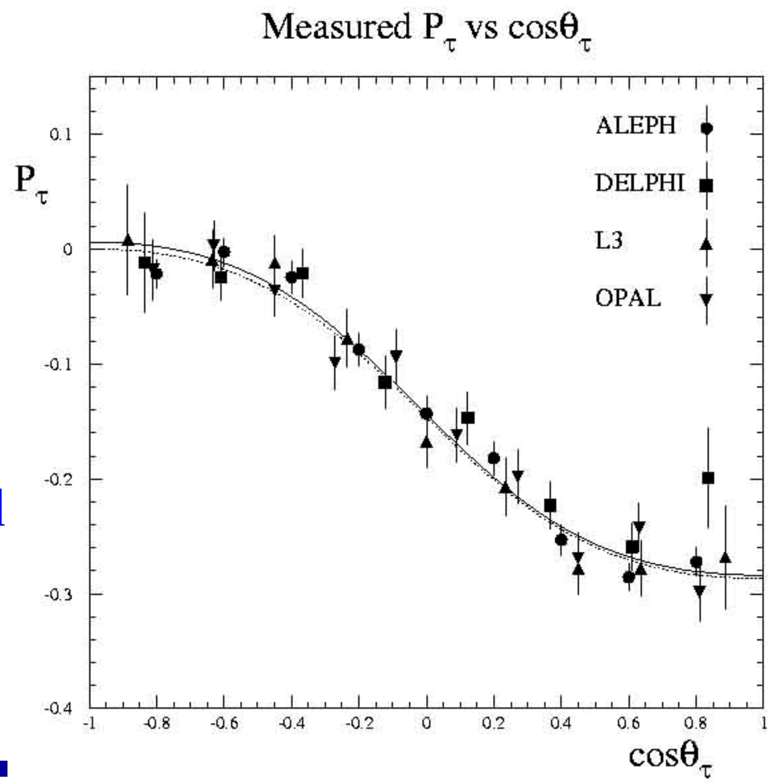
pure Z^0 exchange at the pole

$$P_\tau(\cos\theta_{\tau^-}) = \frac{\langle P_\tau \rangle (1+\cos^2\theta_{\tau^-}) + \frac{8}{3}A_{pol}^{FB}\cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3}A_{FB}\cos\theta_{\tau^-}} = -\frac{\mathcal{A}_\tau (1+\cos^2\theta_{\tau^-}) + 2\mathcal{A}_e \cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta_{\tau^-}}$$

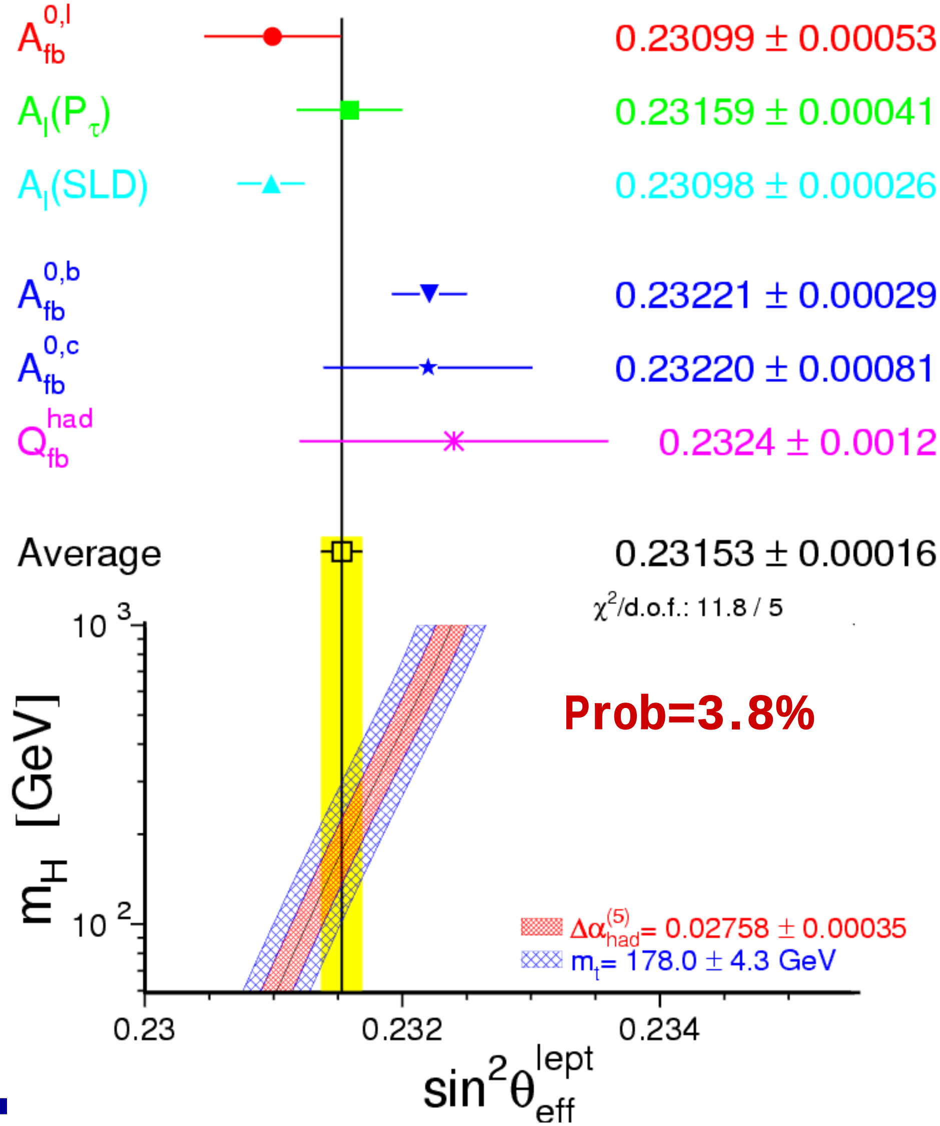
Lines assume
LEP average

solid: no lepton
universality assumed

dashed: assume
lepton universality



Compare different $\sin^2\theta_W$ Measurements



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Hadron Vacuum Polarisation [slides: Davier at Tau06']

<u>Define:</u> photon vacuum polarization function $\Pi_\gamma(q^2)$

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

<u>*Ward identities*</u>: only vacuum polarization modifies electron charge

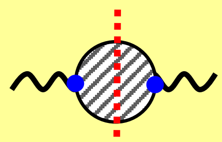
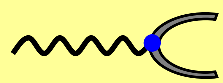
$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)} \qquad \text{with:} \qquad \Delta\alpha(s) = -4\pi\alpha\,\mathrm{Re}\left[\Pi_\gamma(s) - \Pi_\gamma(0)\right]$$

Leptonic $\Delta\alpha_{\mathrm{lep}}(s)$ calculable in QED. However, quark loops are modified by long-distance hadronic physics, cannot (yet) be calculated within QCD (!)

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

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

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

Im[] $\propto$ |  hadrons $|^2$

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

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

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Compare different $\sin^2\theta_W$ Measurements

$\sin^2\theta_{eff}^{lept}$ from only

leptons 0.23113 ± 0.00021 $\text{Prob}(\chi^2) = 0.45$ only LEP=0.23136 ± 0.00032

hadrons 0.23222 ± 0.00027 $\text{Prob}(\chi^2) = 0.99$

new lepton measurements should be at least 0.00021 to have a big impact (apart from testing running)

$$\sin^2\theta_{eff}^{lept}\text{(leptonic couplings only)}$$
$$-\ \sin^2\theta_{eff}^{lept}\text{(leptonic\&hadronic couplings)}$$

$$=(0.23113 \pm 0.00021)-(0.23222 \pm 0.00027)$$
$$=-0.00109 \pm 0.00034 \Rightarrow 3.2\sigma$$

Note: if A_{LR} is ignored, still get -2.0σ

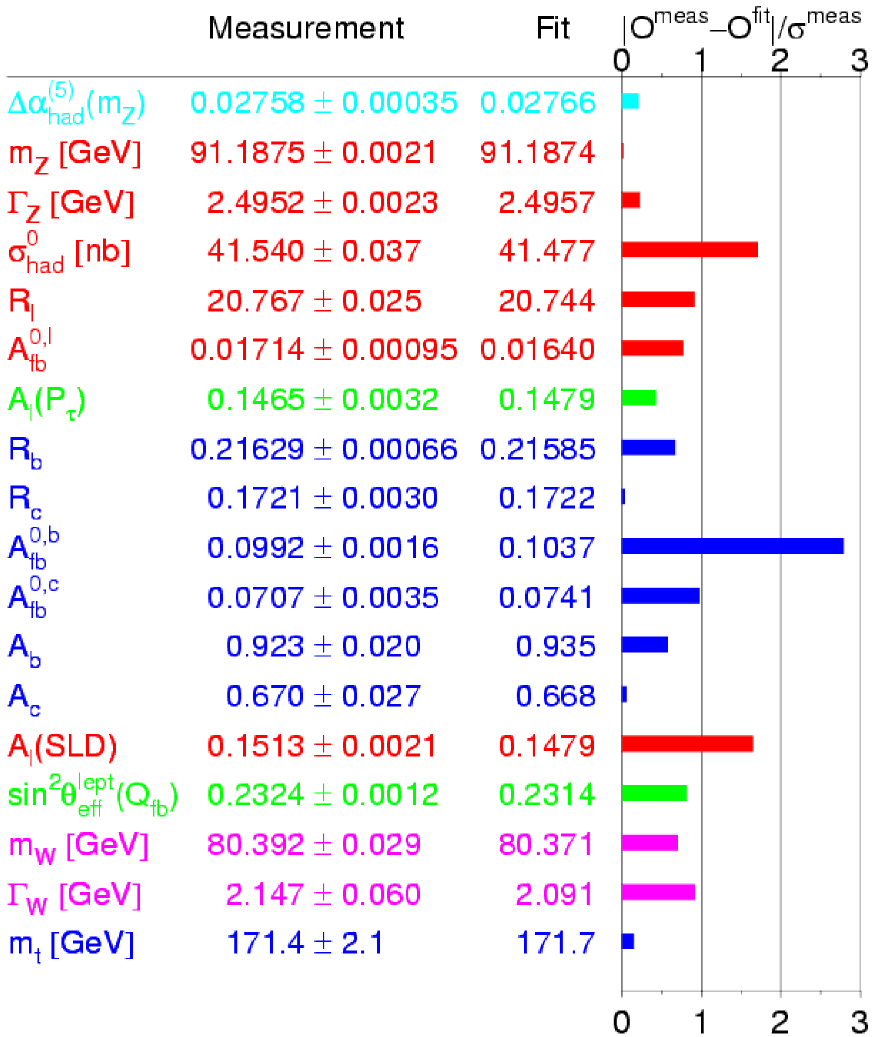
if $A_{FB}^{0,b}$ is ignored, get -1.6σ

Despite tremendous effort looking for unaccounted systematic effect, particularly for $A_{FB}^{0,b}$, none has been identified

Remaining Possibilities:

- statistical fluctuation
- sign of new physics

Standard Model Fits: Summer '06



	all Z-pole data plus m_t, m_W, Γ_W
m_t [GeV]	$171.7^{+2.0}_{-2.0}$
m_H [GeV]	85^{+39}_{-28}
$\log(m_H/\mathrm{GeV})$	$1.93^{+0.16}_{-0.17}$
$\alpha_S(m_Z^2)$	0.1186 ± 0.0027
$\chi^2/\mathrm{d.o.f.}\ (P)$	17.8/13 (17%)
$\sin^2\theta^{lept}_{eff}$	0.23141 ± 0.00014
$\sin^2\theta_W$	0.22316 ± 0.00031
m_W [GeV]	80.371 ± 0.016

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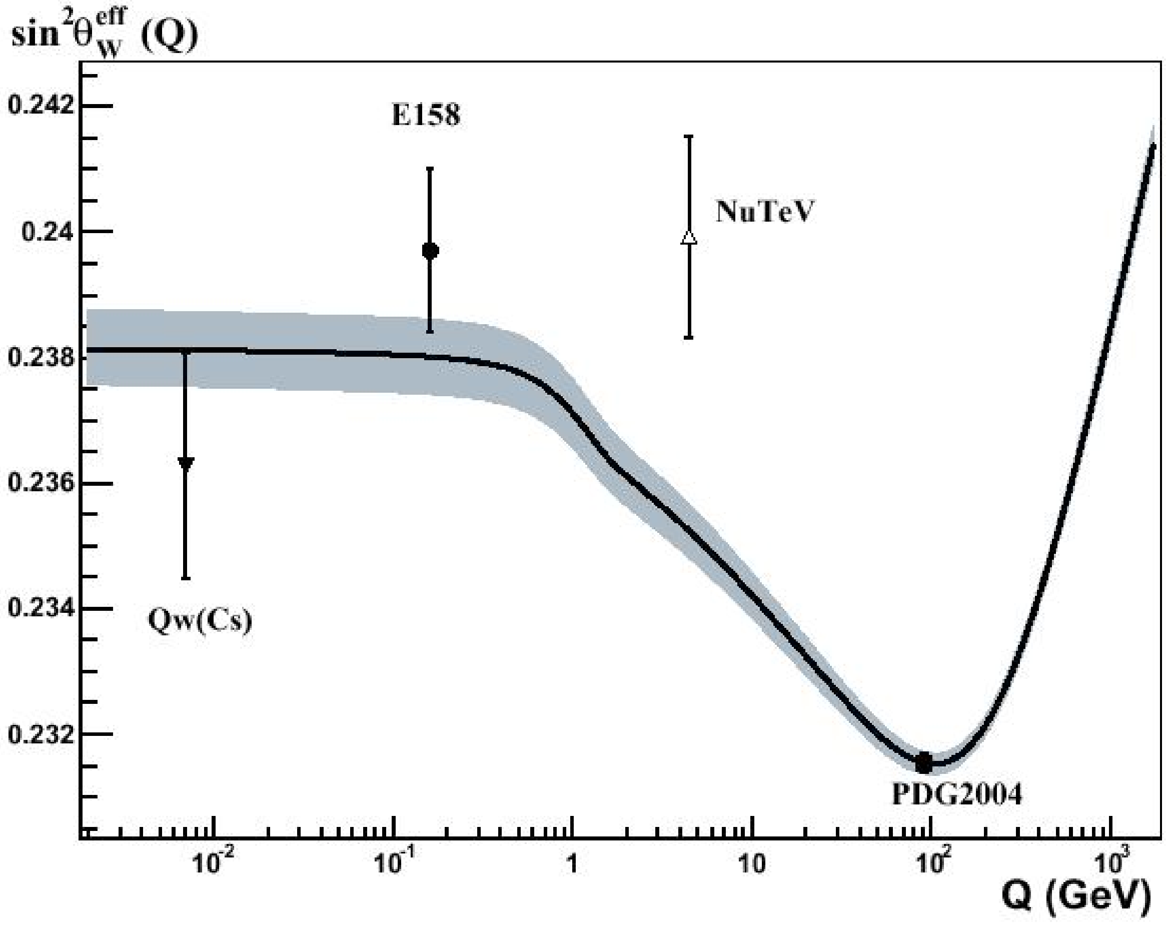
Standard Model Fits: Summer '06

	Measurement with Total Error	Standard Model High-Q^2 Fit	Pull
APV [213]			
$Q_W(\text{Cs})$	-72.74 ± 0.46	-72.907 ± 0.033	0.4
Møller [215]			
$\sin^2\theta_{\overline{\text{MS}}}(m_Z)$	0.2330 ± 0.0015	0.23112 ± 0.00013	1.3
νN [216]			
$g^2_{\nu \text{Lud}}$	0.30005 ± 0.00137	0.30389 ± 0.00017	2.8
$g^2_{\nu \text{Rud}}$	0.03076 ± 0.00110	0.03011 ± 0.00003	0.6

Table 10.3: Summary of measurements performed in low-Q^2 reactions, namely atomic parity violation, e^-e^- Moller scattering and neutrino-nucleon scattering. The SM results and the pulls (difference between measurement and fit in units of the total measurement error) are derived from the SM fit including all high-Q^2 data (Table 10.2, column 4) with the Higgs mass treated as a free parameter.

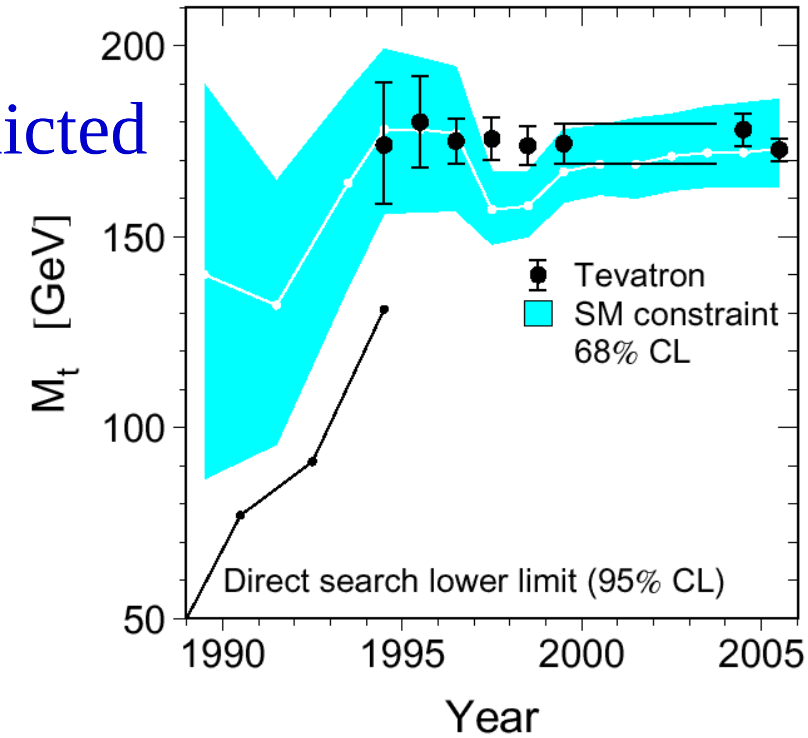
Running of $\sin^2\theta_W$



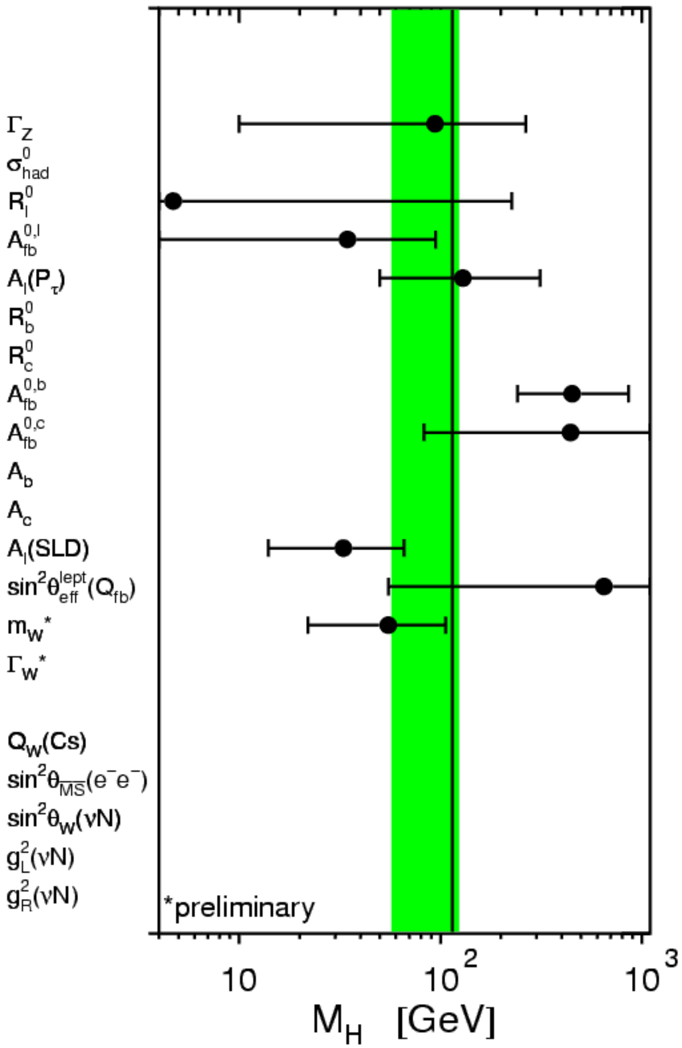
Z^0 EW Precision $\sin^2\theta_W \rightarrow M_{top}$

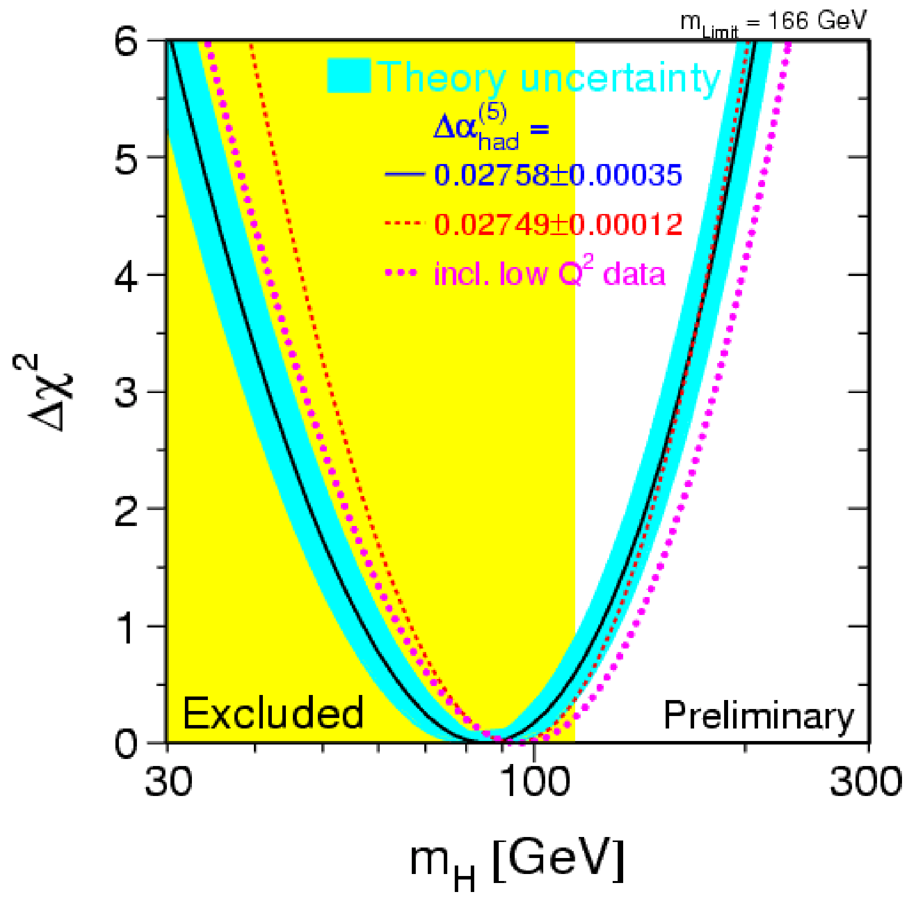
precision Mz and asymmetry measurements at LEP/SLD predicted M_{top} years prior to the Tevatron discovery.

An important milestone in EW physics: quantum field theory can successfully describe weak interaction physics



Predicting M_{Higgs}





Measuring $\sin^2\theta_W$ at LHC

A_{FB} in Drell-Yan can be used to measure $\sin^2\theta_W$

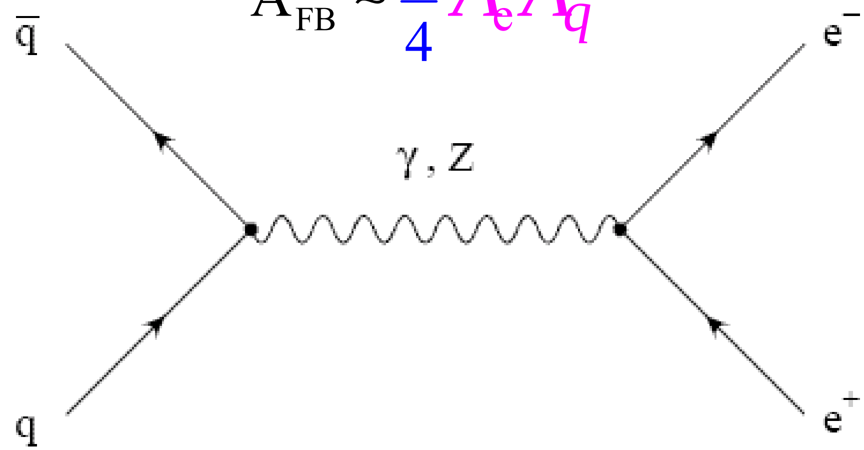
@LHC p-p collisions $\rightarrow \bar{q}$ is a sea-quark
q is a valence quark

At parton level in CM:

$$\frac{d\hat{\sigma}}{d\cos\theta^*} = \frac{\alpha^2}{4s}\left[A_0\left(1+\cos^2\theta^*\right)+A_1\cos\theta^*\right]$$

A_0 & A_1 determined by EW couplings of initial- and final-state fermions

$$A^q_{FB} \sim \frac{3}{4} A_e A_q$$



$$\left.\begin{aligned} \hat{\sigma} &= \frac{4\pi\alpha^2}{3s}A_0 \\ A_{FB} &= \frac{3}{8}\frac{A_1}{A_0} \end{aligned}\right\}$$ "observables"

$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim \left|\gamma_s + Z_s + \text{New Physics}\right|^2$$

New Physics observable in amplitude or interference with γ & Z

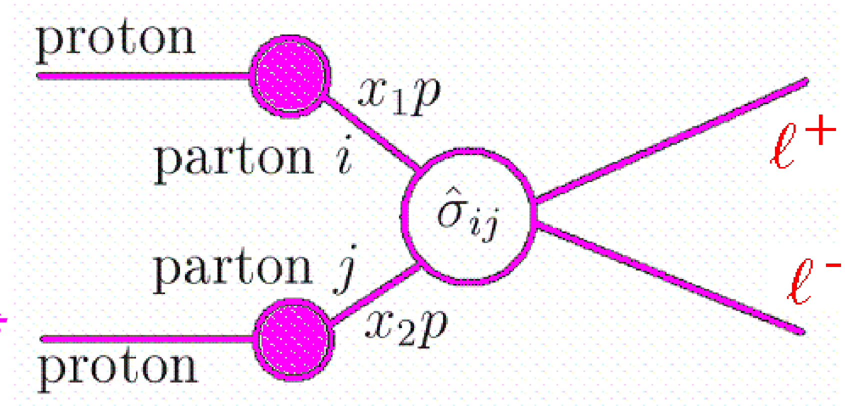
Measuring $\sin^2\theta_W$ at LHC

Partons cross sections folded with

parton distribution functions (PDFs)

$$\frac{d^2\hat{\sigma}\left(pp \to \ell_1\ell_2\right)}{dM_{\ell_1\ell_2}dy} \sim$$

$$\sum_{ij}\left(f_{i/p}(x_1)\, f_{j/p}(x_2) + f_{j/p}(x_1)\, f_{i/p}(x_2)\right)\hat{\sigma}$$



$\hat{\sigma}$: cross section for $q_1\bar{q}_2 \to \ell_1\ell_2$

$M_{\ell_1\ell_2} = \sqrt{\tau s} = \sqrt{\hat{s}}$: invariant mass of $\ell_1\ell_2$

$y = \frac{1}{2}\ln\left(\frac{E + p_Z}{E - p_Z}\right)_{\ell_1\ell_2}$: rapidity of $\ell_1\ell_2$

$$\left.\begin{array}{l} x_1 = \sqrt{\tau}e^{y} \\ x_2 = \sqrt{\tau}e^{-y} \end{array}\right\}\text{parton momentum fractions}$$

$f_{i/p}(x_k)$: probability to find parton i with momentum fraction x_k in the proton

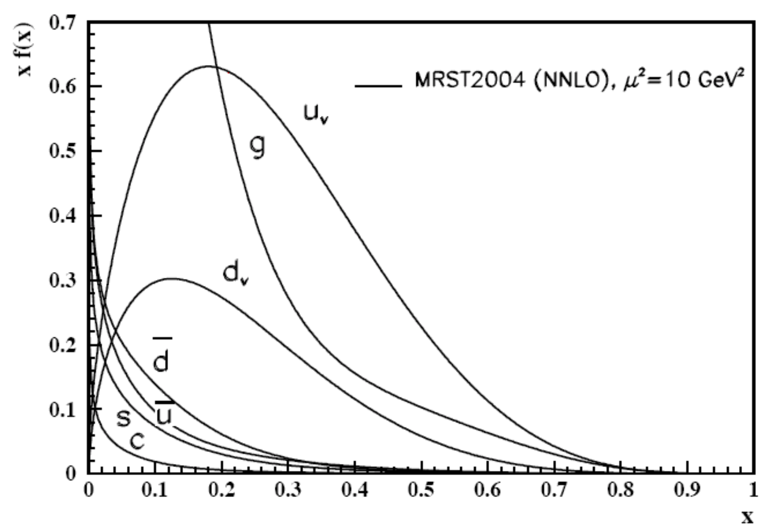


Figure 16.4: Distributions of x times the unpolarized parton distributions $f(x)$ (where $f = u_v, d_v, \overline{u}, \overline{d}, s, c, g$) using the NNLO MRST2004 parameterization [13] at a scale $\mu^2 = 10\ \mathrm{GeV}^2$.

Measuring $\sin^2\theta_W$ at LHC

Recall

- particle production is ~constant as function of

rapidity, $y = \frac{1}{2}\ln\left(\frac{E + p_Z}{E - p_Z}\right)$

- difference in rapidity of two particles is independent

of Lorentz boosts along the beam axis

At the parton level, these boosts are unknown at hadron colliders

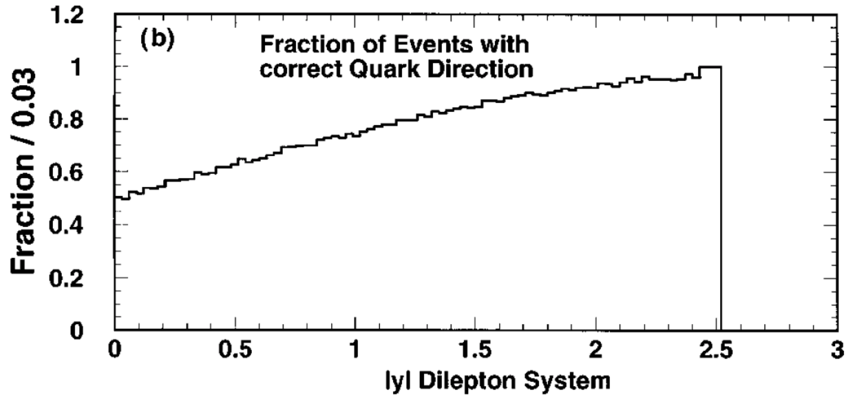
Pseudorapidity, η, is numerically close to y, but is only dependent on the angle relative to the beam axis, θ

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Measuring $\sin^2\theta_W$ at LHC

$$\sigma_{\mathrm{F\pm B}}(y,M) = \int_0^1 \sigma_{\ell\ell} d\cos\theta^* \pm \int_0^1 \sigma_{\ell\ell} d\cos\theta^*$$

$$A_{\mathrm{FB}}^{\ell}(y,M) = \frac{\sigma_{\mathrm{F-B}}(y,M)}{\sigma_{\mathrm{F+B}}(y,M)}$$



M. Dittmar PRD 55(2007)

A_{FB}^{ℓ} defined in terms of $\cos\theta^*$, with respect to q direction

In p-p collisions at LHC, direction of q needs to be inferred

from kinematics of $\ell^+\ell^-$ system:

antiquarks come from sea, quarks are valence or sea

$\Rightarrow$ $\ell^+\ell^-$ boost direction preferentially along quark direction

$\Rightarrow$ rapidity is used as measure of quark direction

UVic

Measuring $\sin^2\theta_W$ at LHC

ATLAS study by Sliwa,Riley,Baur reported in hep-ph/0003275 using PYTHIA 5.7 & JETSET 7.2

$p_T^{electron} > 20 GeV$

$85.2 GeV < M(e^+e^-) < 97.2 GeV$

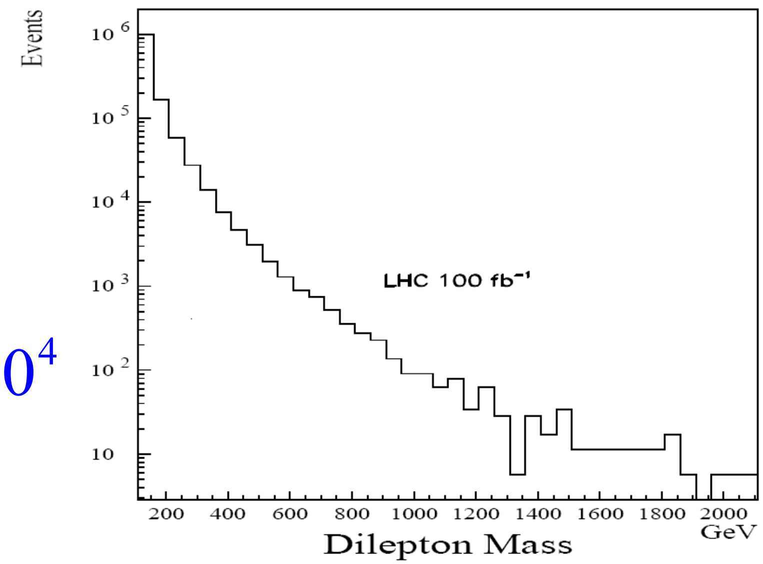
at least 1 electron with $|\eta| \leq 2.5$:

Electron ID eff. ~70%; jet rejection $>10^4$

allow 2nd electron up to $|\eta| \leq 4.9$:

Electron ID eff. ~50%;

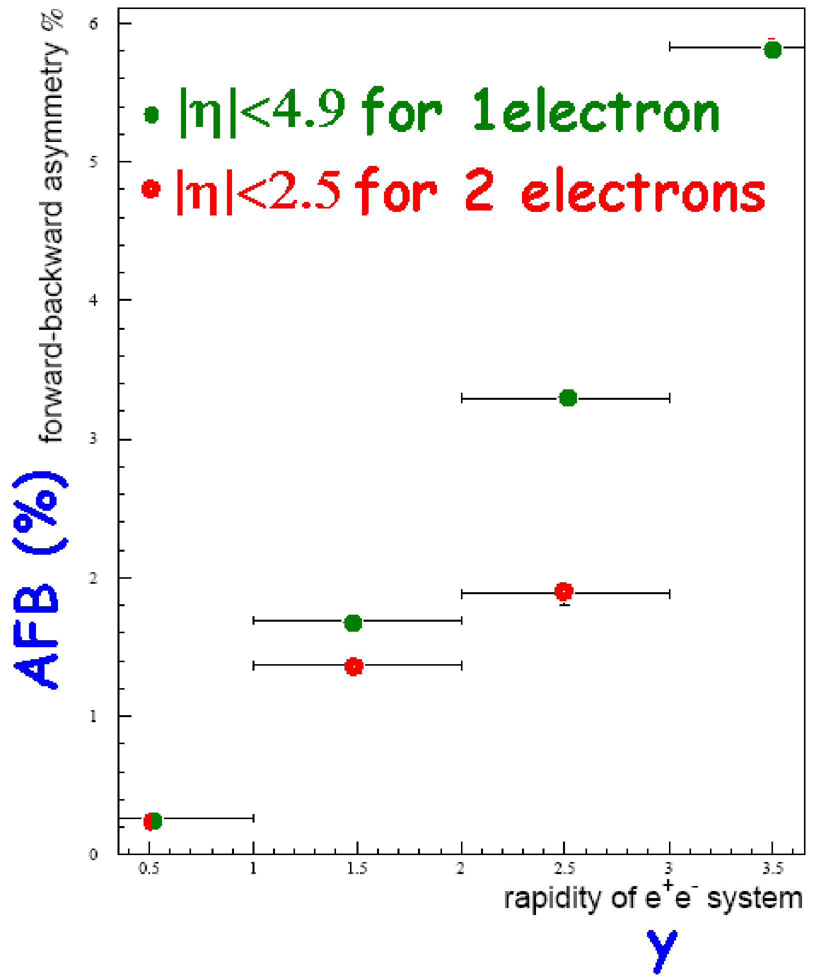
η – cut dependent jet rejection



Measuring $\sin^2\theta_W$ at LHC

Dependence of A_{FB} on rapidity at LHC and η cuts on electron

note: A_{FB} from $Z \to \mu^+\mu^-$ as for $|\eta|<2.5$ for both μ



Measuring $\sin^2\theta_W$ at LHC

Connecting to $\sin^2\theta_W$:

$$A_{FB} = b\left(a - \sin^2\theta_{eff}^{lept}\left(M_Z^2\right)\right)$$

$$a^{O(\alpha^3)} = a^{Born} + \Delta a^{QED} + \Delta a^{QCD}$$

$$b^{O(\alpha^3)} = b^{Born} + \Delta b^{QED} + \Delta b^{QCD}$$

Cuts	a^{Born}	Δa^{QED}	Δa^{QCD}	$a^{O(\alpha^3)}$	b^{Born}	Δb^{QED}	Δb^{QCD}	$b^{O(\alpha^3)}$
$\lvert\eta\rvert < 2.5$ both $e^\pm$	.2481	.0025	-.0026	.2480	0.48	-0.01	-0.16	0.31
$\lvert\eta\rvert < 2.5$ both $e^\pm$ $\lvert y(e^+e^-)\rvert > 1.0$	.2503	-.0009	-.0069	.2425	0.74	0.05	-0.03	0.76
$\lvert\eta\rvert < 2.5$ one $e^\pm$ $\lvert\eta\rvert < 4.9$ the other $e^\pm$	.2483	-.0005	-.0015	.2463	1.18	0.15	-0.10	1.23
$\lvert\eta\rvert < 2.5$ one $e^\pm$ $\lvert\eta\rvert < 4.9$ the other $e^\pm$ $\lvert y(e^+e^-)\rvert > 1.0$	.2486	.0011	-.0028	.2469	1.66	0.01	-0.04	1.63

Vic

Measuring $\sin^2\theta_W$ at LHC

Table 9: Statistical precision which can be obtained on $\sin^2\theta^{\rm lept}_{\rm eff}(M_Z^2)$ from measurements of A_{FB} in $Z \to ee$ from one LHC experiment with 100 fb^{-1}. Results are given for different jet rejection factors ρ for the forward calorimetry $2.5 < |\eta| < 4.9$.

Cuts	ρ	A_{FB} (%)	ΔA_{FB} (%)	$\Delta \sin^2\theta^{\rm lept}_{\rm eff}(M_Z^2)$
$|\eta| < 2.5$ both $e^\pm$	-	0.774	0.020	6.6×10^{-4}
$|\eta| < 2.5$ both $e^\pm$ $|y(e^+e^-)| > 1.0$	-	1.66	0.030	4.0×10^{-4}
$|\eta| < 2.5$ one $e^\pm$ $|\eta| < 4.9$ the other $e^\pm$	10^4	2.02	0.017	1.4×10^{-4}
	10^2	1.98	0.018	1.4×10^{-4}
	10^1	1.68	0.021	1.7×10^{-4}
$|\eta| < 2.5$ one $e^\pm$ $|\eta| < 4.9$ the other $e^\pm$ $|y(e^+e^-)| > 1.0$	10^4	3.04	0.022	1.35×10^{-4}
	10^2	2.94	0.023	1.41×10^{-4}
	10^1	2.31	0.030	1.83×10^{-4}

$\mu\mu$

hep-ph/0003275

Measuring $\sin^2\theta_W$ at LHC

Systematic uncertainties:

- **PDFs: lepton acceptance & radiative corrections**
- **Lepton acceptance & reco eff vs Y (need <0.1%, PDFs an issue)**
- **Higher order QCD & EW corrections**
- **Mass Scale (AFB varies with lepton pair mass)**

Measuring $\sin^2\theta_W$ at LHC

Systematic uncertainties:

Biggest worry is

- **PDFs: lepton acceptance & radiative corrections**

Studied by PDFs (MRST, CTEQ3, CTEQ4) stat. limited study suggests agreement at ~1% on A_{fb} [but these PDFs are correlated]. Moreover, need x~10 better error, to keep it small cf stat error.

(note: this is more demanding than for $A_{FB}^{0,b}$ since the sensitivity to $\sin^2\theta_W$, b factor, is much lower.)

simultaneous fits for $\sin^2\theta_W$ and PDFs?

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Measuring $\sin^2\theta_W$ at LHC

Assume something approaching the statistcal error can be achieved:

this is in fact complementary to the e^-e^- measurement because it is sensitive to quark and lepton couplings, not just lepton couplings: if LEP/SLD "discrepancy" is from new physics *AND* related to quark vs lepton NC couplings,that new physics should show up here as well:

this LHC measurement is ~ Q_{FB}^{had} at LEP

Measuring $\sin^2\theta_W$ at LHC

But LHC will also measurement the asymmetry well above the Z measuremests at several % level [M.Dittmar PRD 55 '95]

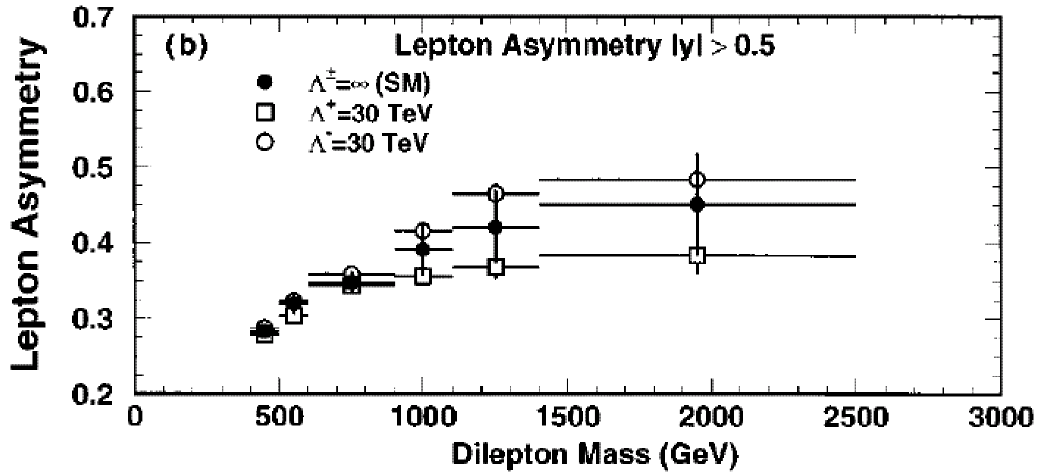

FIG. 3. Expected dilepton mass distributions (a) and lepton symmetries (b) for the standard model and for quark compositeness with different $\Lambda^{\pm}$ values.

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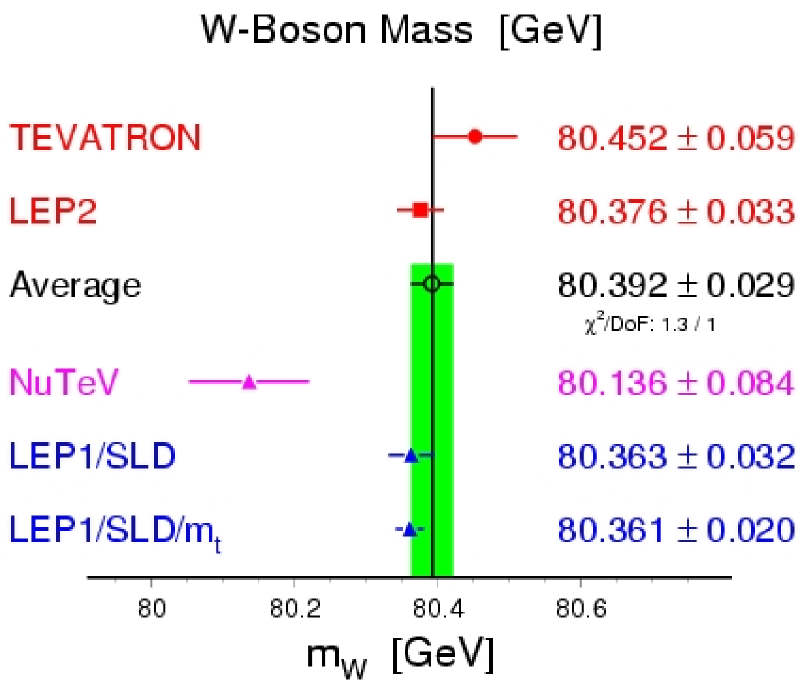
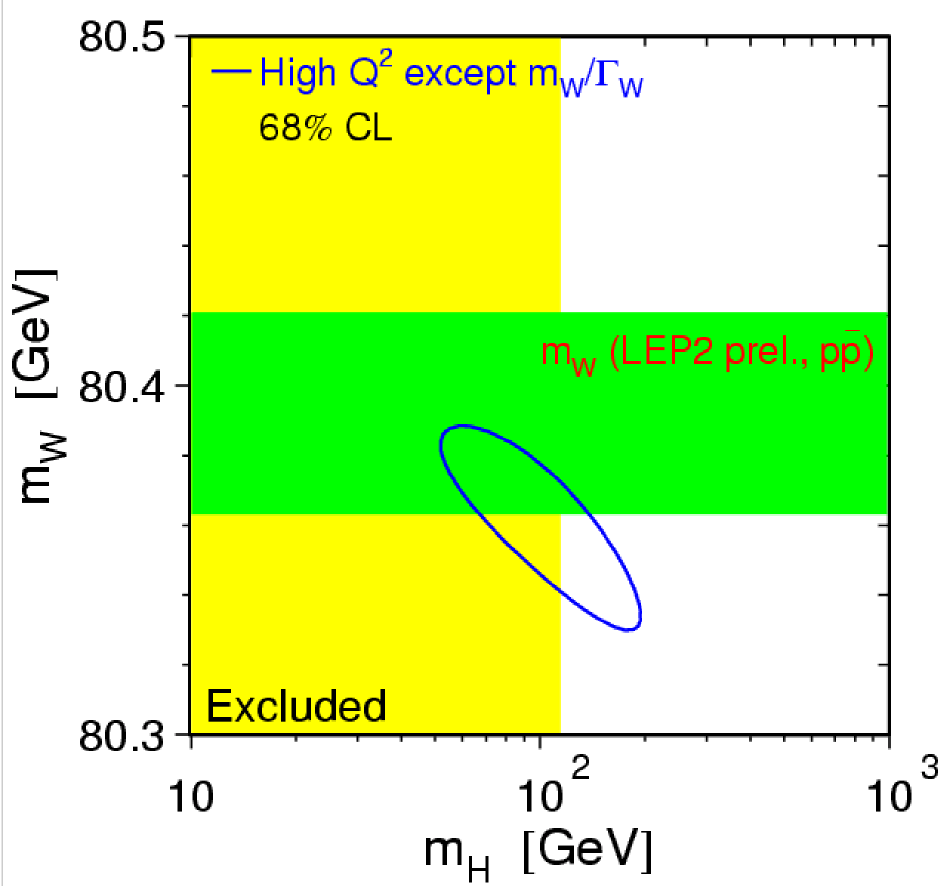
Mw @ LEP & Tevatron

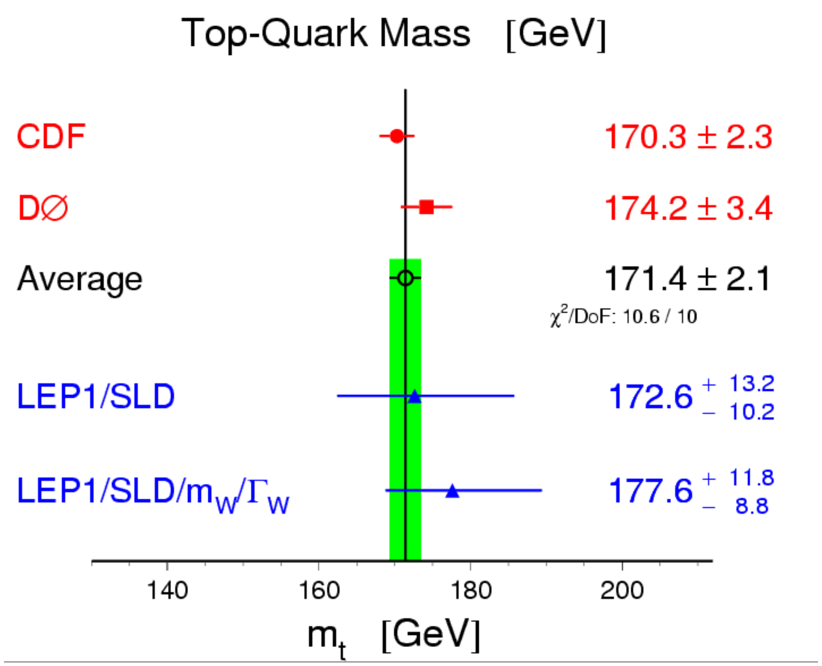
- Current Mw measurements give EW constraints on e.g. M_{Higgs}… complementary to $\sin^2\theta_W$

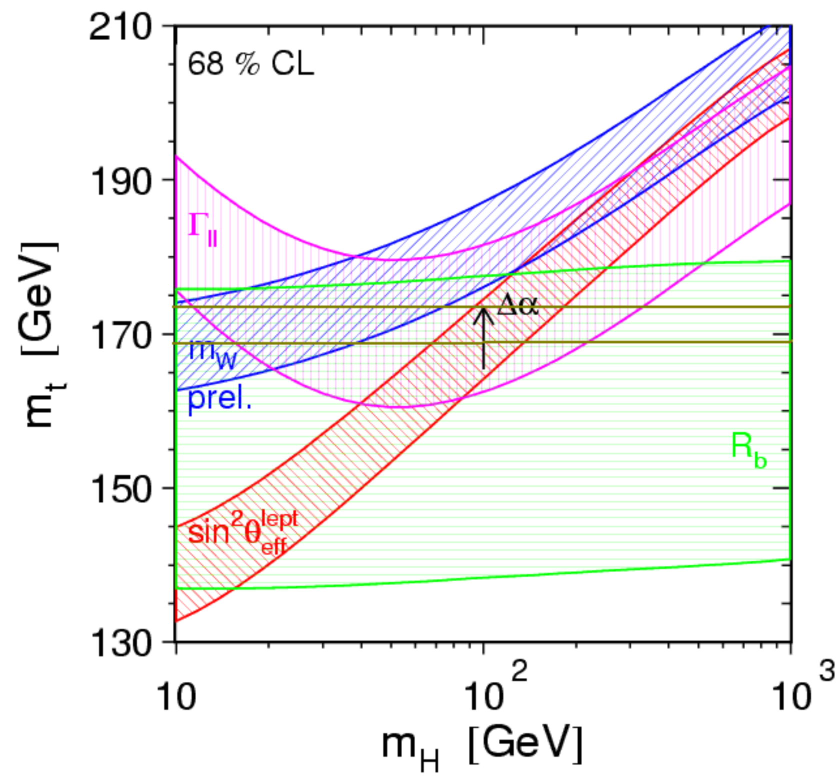




Mtop @ Tevatron

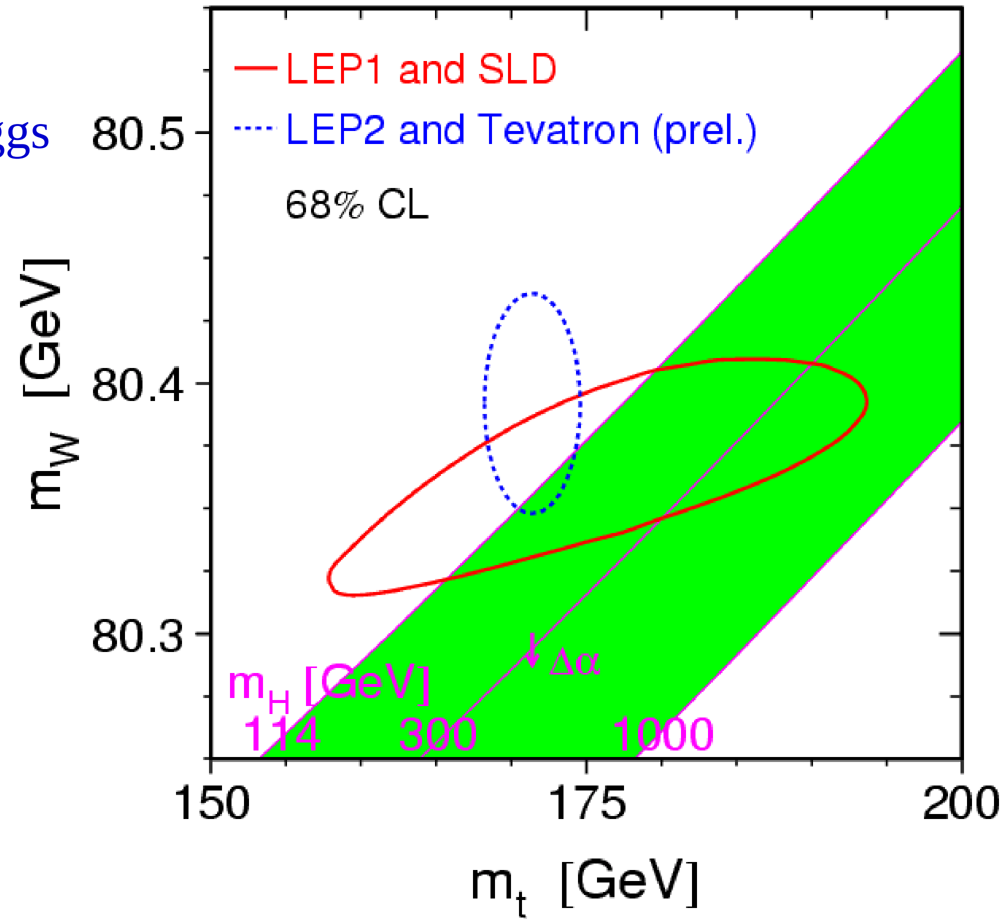
- Current Mtop measurements give EW constraints on e.g. M_{Higgs} complementary to $\sin^2\theta_W$





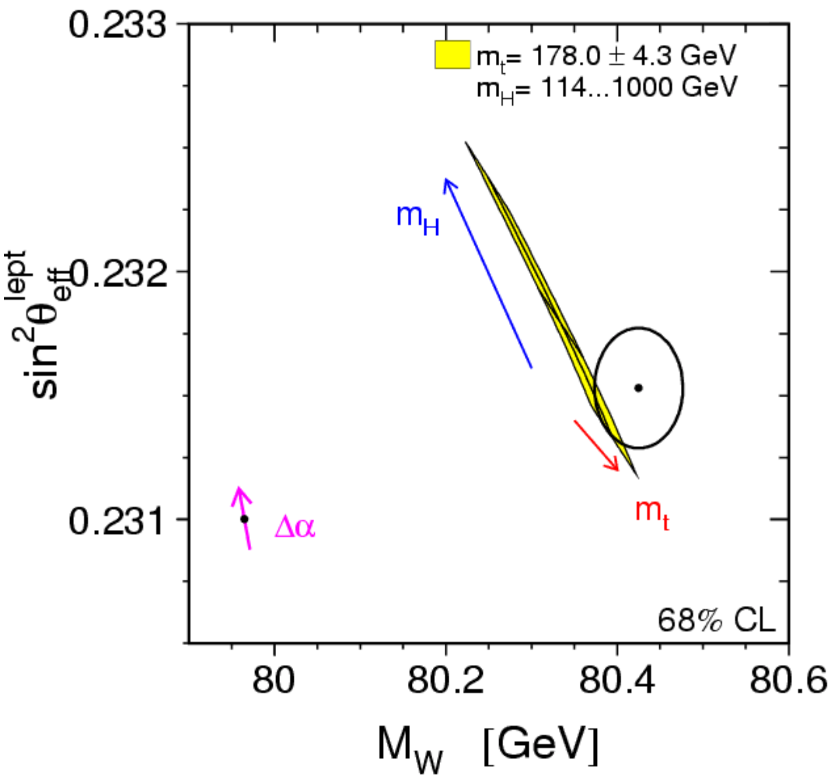
Mw@LEP and Mw&Mtop@Tevatron

- Mw & Mtop give complementary EW constraints on e.g. M_{Higgs} independent of $\sin^2\theta_W$ measurements



Mw at LEP & Tevatron

- Mw & Mtop give constraints on Mhiggs… complementary to $\sin^2\theta_W$



Mw at LHC expected

- Mw & Mtop give constraints on Mhiggs… complementary to $\sin^2\theta_W$
- Uncertainties are expected to be significantly smaller than LEP & Tevatron values

Mw at LHC

$$M_W = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}} \cdot \frac{1}{\sin\theta_W \sqrt{1-\Delta r}} \longrightarrow f(m_{top}^2, \log(M_H))$$

- precision test of the Standard Model combined with m_{top} and direct measurement of the Higgs mass
- for equal Δm_{top} and ΔM_W contributions to M_H indirect measurement

$$\Delta M_W \sim \mathbf{0.7 \times 10^{-2}\, \Delta m_{top}}$$

- LHC: $\Delta m_{top} < 2$ **GeV** $\Rightarrow \Delta M_W < 15$ **MeV**

→ constrain M_H to 30%

- Tevatron + LEP2 : $\Delta M_W = 30$ MeV
  Tevatron Run 2: expected $\Delta M_W \sim 30$MeV with 2 fb^{-1}

from M. Malberi ICHEP '06

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Mw@Tevatron: reality check for LHC

- measurement from transverse mass $M^T = \sqrt{2\, p_l^T\, p_\nu^T (1 - \cos\phi_{l\nu})}$
- Tevatron Run 1, $\mathcal{L}$~120 pb^{-1} :
  ΔM_W = 59 MeV combined (79 CDF, 84 D∅)
- CDF Run 2 , $\mathcal{L}$~200 pb^{-1}:
  ΔM_W = 76 MeV e-μ channel combined

source of uncertainty	CDF Run 2 Electrons (MeV)	CDF Run 2 Muons (MeV)
Statistics	45	50
Lepton scale and resolution	70	30
Recoil scale and resolution	50	50
PDFs	15	15
Radiative decays	15	20
pT(W)	13	13
W width	12	12
Backgrounds	20	20
Total	105	85

hep-ph/0506016

dominant source of uncertainty in the measurement!

M. Malberti ICHEP 06, Moscow, 27/07/2006

UVic

W mass: goals at the LHC

- aimed precision at LHC: $\Delta M_W = 15$ MeV

  $\Rightarrow$ need to keep all contributions to W mass uncertainty below **~10 MeV**

- Statistical uncertainty: not an issue at the LHC

  $\sigma(pp \to W \to l\nu) \sim 30$ nb $(l = e, \mu) \Rightarrow$ 3×10^8 Ws with $\mathcal{L} = 10$ fb^{-1}

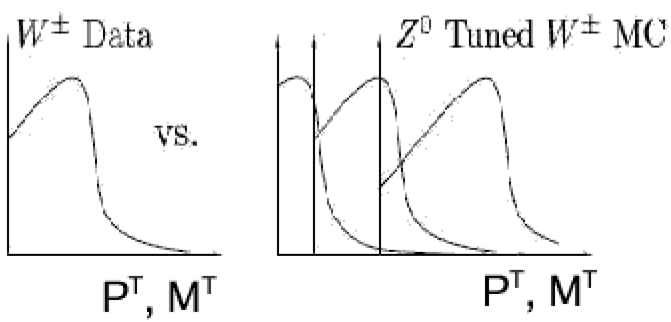
- **Challenging: energy/momentum scale** $\Rightarrow$ **10 MeV/100 GeV $\Rightarrow \delta p/p \sim O(10^{-4})$!**

- Take advantage from the large Z sample to constraint systematics

  $\sigma(pp \to Z \to ll) \sim 3$ nb $(l = e, \mu) \Rightarrow$ 3×10^7 Zs with $\mathcal{L}$=10 fb^{-1}

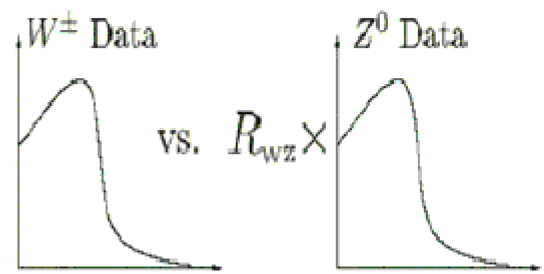
Strategies to measure W mass

Traditional method
(see Tevatron)



- fit W data with **MC templates** generated at different values of M_W
- requires very good modelling
  - physics
  - detector performances

W/Z ratio method



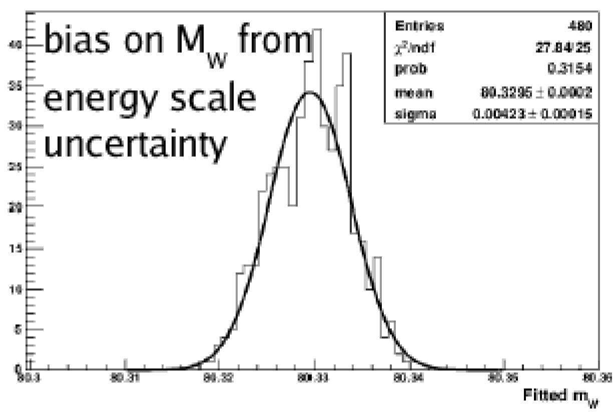
- use **Z events** scaled with M_W/M_Z **as templates**
- limited by Z-statistics at Tevatron, affordable at LHC!
- common uncertainties reduced in the ratio

W mass: traditional method (ATLAS)

- *transverse mass, electron channel*
- recent study on lepton energy scale/resolution from Z peak:
  - analysis in energy bins to control non linearities
    5 GeV energy bins in the range 20-140 GeV
  - 2×10^{-4} scale precision in each energy bin with 10 fb^{-1}

    $\rightarrow$ 5×10^{-5} precision on the *absolute* mass scale

    $\rightarrow$ $\Delta M_W \sim$ 4 MeV



source of uncertainty	ΔM_W for 10 fb^{-1} e-channel, M^T (MeV)
Statistics	**< 2**
Background	5
E-p scale	15 (4*)
E-p resolution	5 (<1*)
Recoil model	5
Total instrumental	**<20 (<10)**
PDF	< 10
W width	7
Radiative decays	< 10
pT(W)	5
Total	**<25**

hep-ph/0003275
*ATLAS-PUB-2006-007

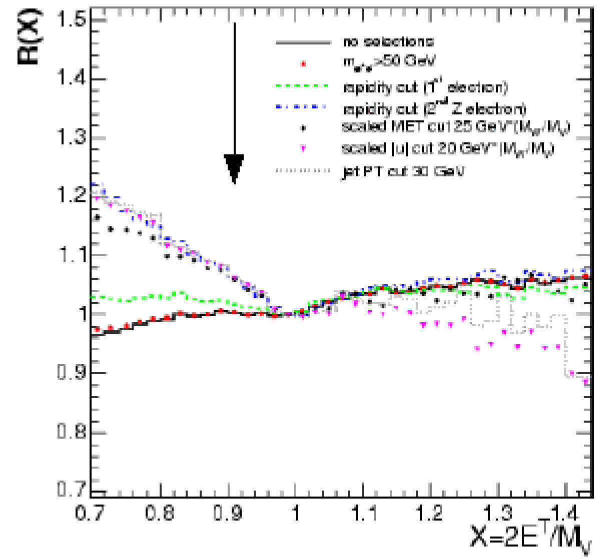
CMS : the 'Scaled Observables' method

CMS NOTE 2006/061

- original idea :
  T.Giele, S.Keller , PR D57 (1998)
- **treat Z as W (ignoring one lepton) and fit W with Z events scaled by**

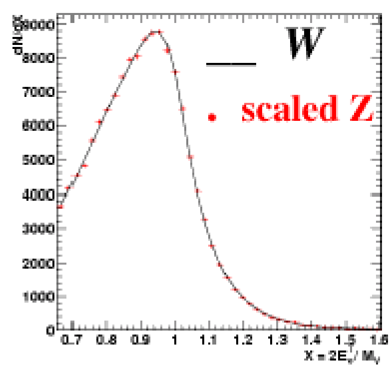
$$R(X) = \frac{d\sigma^W / dX_W}{d\sigma^Z / dX_Z} \qquad X = \frac{M_V^T}{M_V}, \frac{p_{lept}^T}{M_V}$$

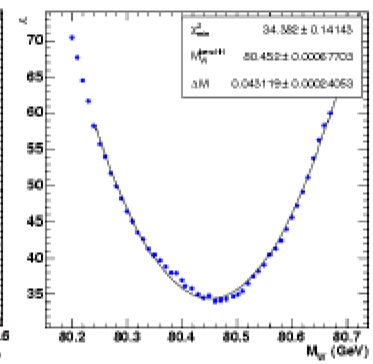
  - R(X) from theory + additional corrections for selections and detector effects
  - event selections scaled with boson masses



- common uncertainties from *experiment* and *theory* reduced
  - cancellation of the uncertainties due to soft gluon emission

  $\Rightarrow$ method relevant for lepton P^T spectrum analysis





Scaled lepton transverse energy

CMS NOTE 2006/061

- statistical precision:
  - limited by Z statistics
- **experimental error reduced**
  - less tight precision requirements:
    e.g.: lepton energy scale to 0.25%
    enough to get $\Delta M_W < 10$ *MeV*
- *uncertainty from $p^T(W)$ largely reduced, but still the limiting factor for 10 fb^{-1}*
  - *preliminary evaluation with DYRAD*
  - *R(X) at different renormalization/fact. scales* $\Rightarrow \Delta M_W < 30$ *MeV*
  - *could be reduced by NNLO calculations*
- prospects for 1 fb^{-1}
  40 MeV (stat.) + 40 MeV (det. syst.)
  + 20 MeV (PDFs) + theory error from $p^T(W)$
  $\Rightarrow$ comparable with current results!

ΔM_W with 10 fb^{-1}

source of uncertainty	scaled E^T e-channel M_W(MeV)
Statistics	15
Background	2
Lepton E-p scale	< 10
E-p resolution	2
Recoil	< 10
Total instrumental	< 20
PDF	< 10
W width	<15
pT(W)	<30

M. Malberti ICHEP 06, Moscow, 27/07/2006

UVic

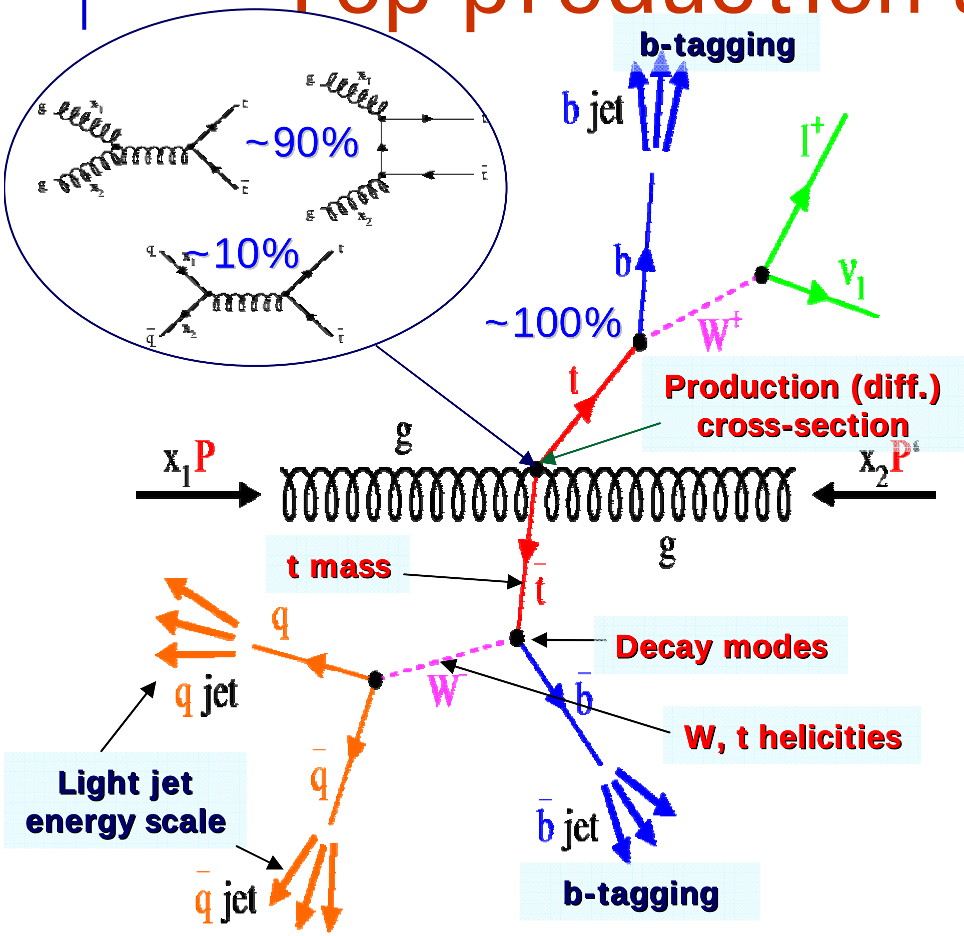
Mw at LHC

Uncertainty on Mass will be dominated by systematics, many of which (such as PDFs,energy scale and resolution) will be determined and themselves limited by statistics.

The GOAL of 15MeV/c^2 looks very challenging at this point, but achieving ~20MeV/c^2 can likely be reached

Top production at the LHC

from R. Chierici ICHEP '06



1. tt is an essential process for commissioning detector and tools
   - jet energy scale, b-tagging calibration

2. tt is a fundamental process for electroweak (precision) measurements
   - the top quark is interesting per se ($m_t \sim 190 m_p$!)
   - m_t, σ_t, q_t, $|V_{tb}|$, σ_{tt}, BR_t, tt, pdfs
   - m_t can greatly help in the indirect constraint of the Standard Model (and new physics !)

3. tt is a fundamental process for the direct search of new physics
   - both production and decay: $X \rightarrow tt$, $t \rightarrow X$, ttX
   - larger couplings with Higgs –new physics?-
   - top is background to many search channels

The LHC will be a top-factory !

- σ_{NLO}~830 pb : 2 tt events per second !
- more than 10 million tt events expected per year
- first physics in 2008 !

	1.96 TeV	14 TeV	
ttbar pairs	$5.06^{+0.13}_{-0.36}$ pb	833^{+52}_{-39} pb	(x170)
Wjj (*)	~1200 pb	~7500 pb	(x6)
bb+other jets (*)	~2.4x10^5 pb	~5x10^5 pb	(x2)

(*) with kinematic cuts in order to better mimic signal
Belyaev, Boos, and Dudko [hep-ph/9806332]

LHC m_t error breakdown

from R. Chierici ICHEP '06

Estimated sensitivities as of today:

	δm_t(stat) (GeV/c^2)	δm_t(syst. instr.) (GeV/c^2) (1)	δm_t(syst. th.) (GeV/c^2) (2)	δm_t (GeV/c^2)
$bqqb\ell\nu$	~0.2	~1.0	~0.6	~1.1
$bqqb\ell\nu$ high p_T	~0.2	~0.9	~1.4	~1.7
$b\ell\nu b\ell\nu$	~0.5	~1.0	~0.3	~1.2
bqqbqq	~0.2	~2.3	~3.5	~4.2
exclusive J/ψ decays	~0.5	~0.5	~1.4	~1.5
via cross-section	~0.1	~0.7	~4.0	~4.1

(1) jet and lepton energy scales, b-tagging, luminosity,...

(2) radiation, fragmentation, MB/UE,...

The key points for reducing the error on m_t will be:

- reduce systematic by using data to calibrate our measurements and to constrain our knowledge on simulation
- combine analyses with a different systematic breakdown
  - → many instrumental systematic errors are analysis correlated
  - → most theory systematic errors are also ATLAS/CMS correlated

⇒ 1 GeV/c^2 error is anyway in reach !

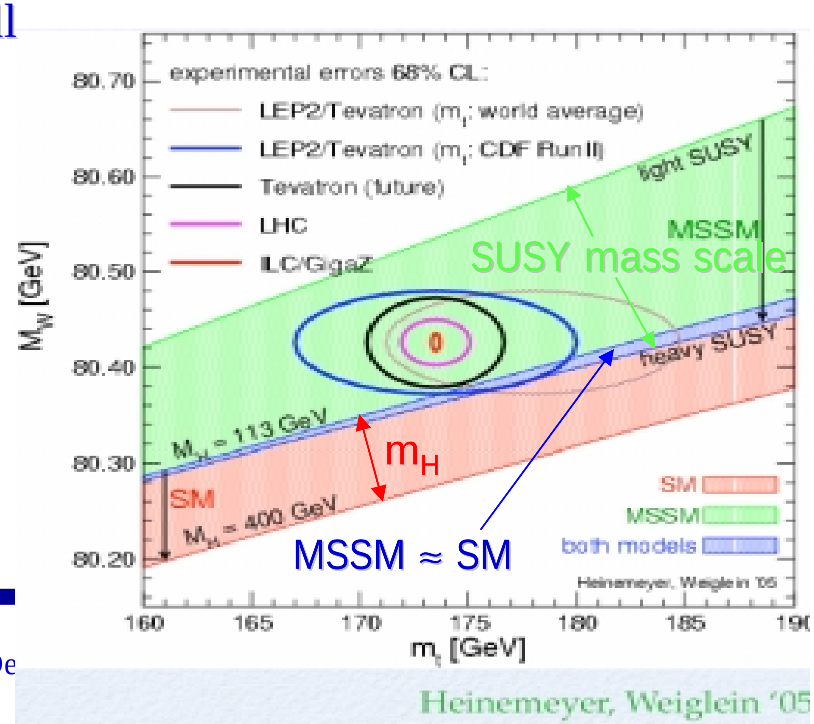
Impact of LHC W and Top measurements

from R. Chierici ICHEP '06

- The experiments have now presented their realistic potential on top physics measurements. Many ideas around on how to determine the top mass.

- By combining all analyses, an estimation of $\delta m_t \sim 1 \mathrm{GeV}/c^2$ is realistic and totally dominated by systematic error.
  - → Conservatively estimated, especially when due to theoretical uncertainties
  - → The use of data for understanding detector and simulation will be essential

- A precise measurement of the top quark mass will allow to:
  - → improve detector understanding
  - → constrain standard physics
  - → look for presence of new physics
  - → constrain new physics !

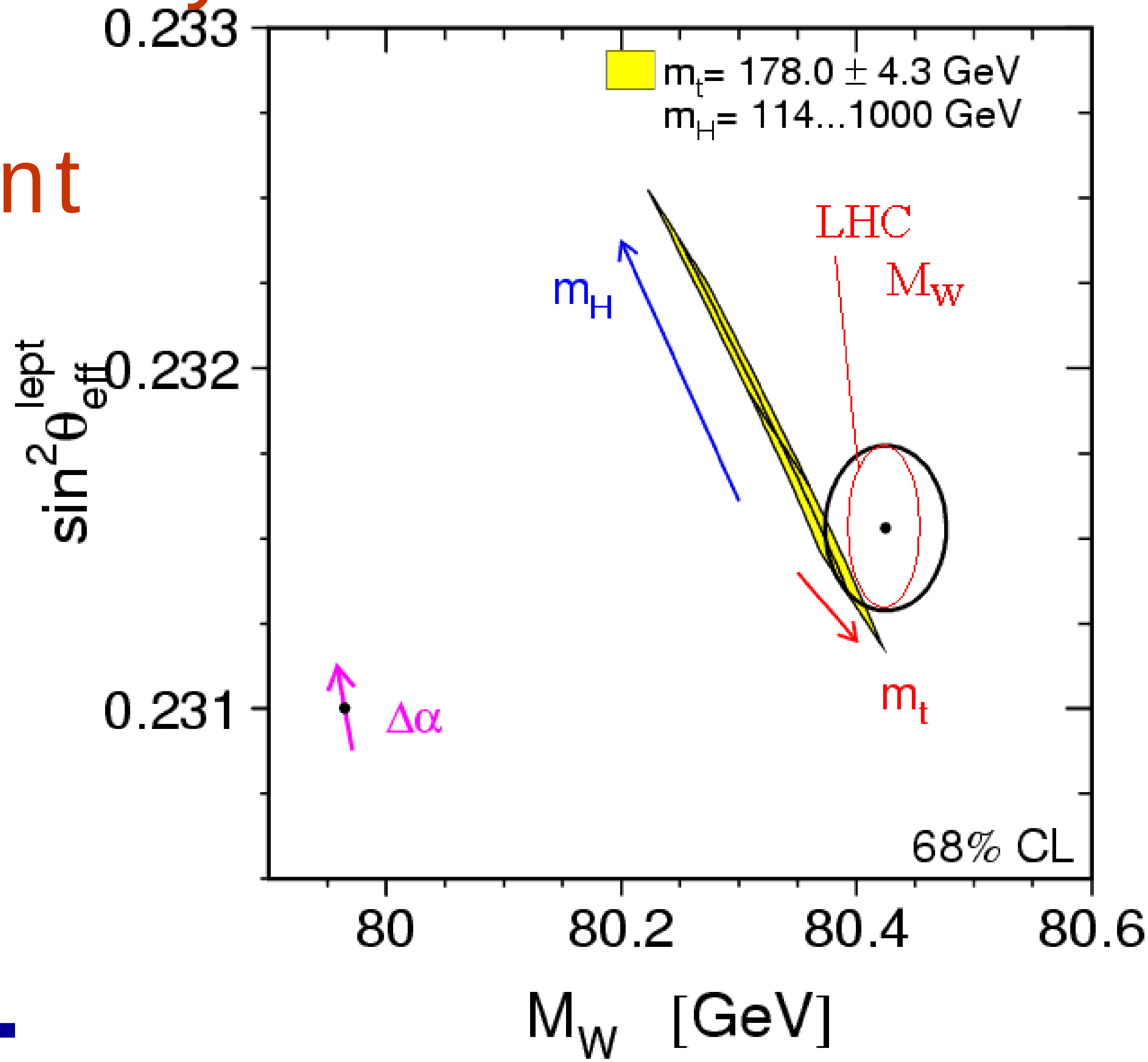


Assuming $\delta m_W = 15 \mathrm{MeV}/c^2$ and also $\Delta\alpha_{had} = 0.00012$

$\rightarrow (\delta m_H / m_H \approx 25\%)$

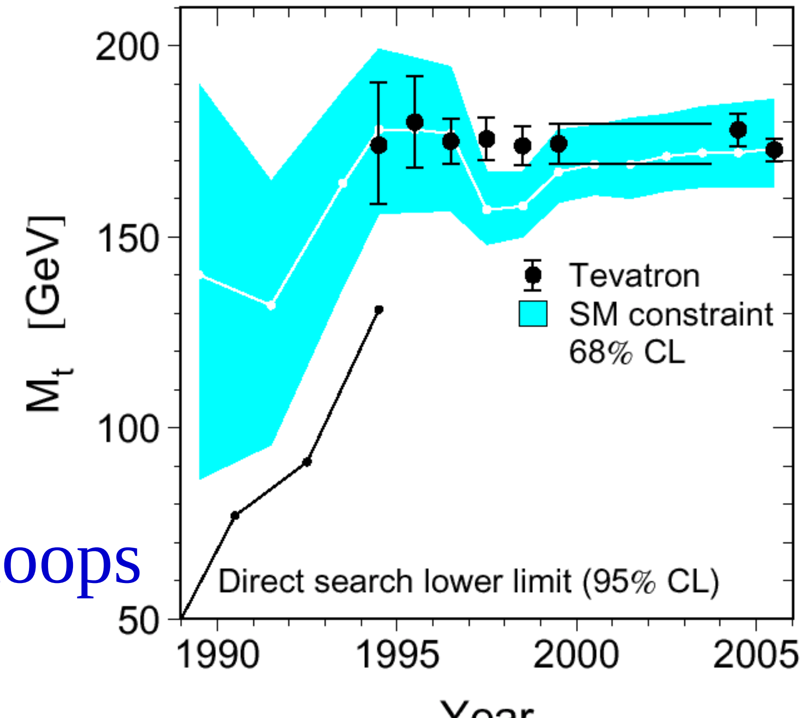
⇒ Chances of ruling out the SM...

Complementarity of $\sin^2\theta_W$ Measurement



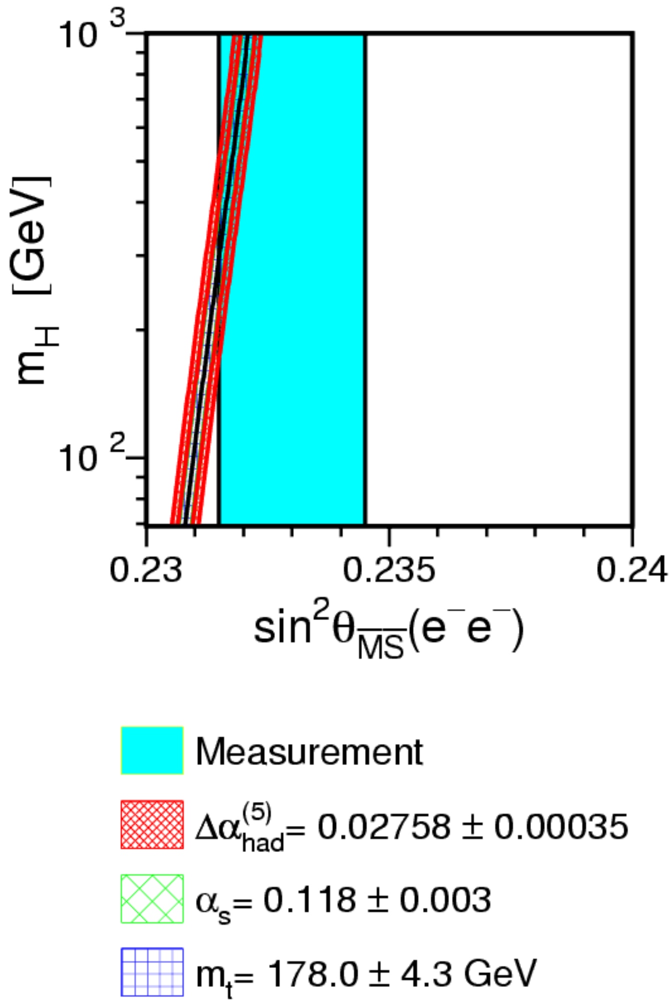
LHC expected to measure M_{Higgs}

Complementarity with precision EW:
predict M_{Higgs} with precision,
just as M_{top} was predicted;
if Mtop not where Z^0 analyses said it should be…
then something else is in those loops



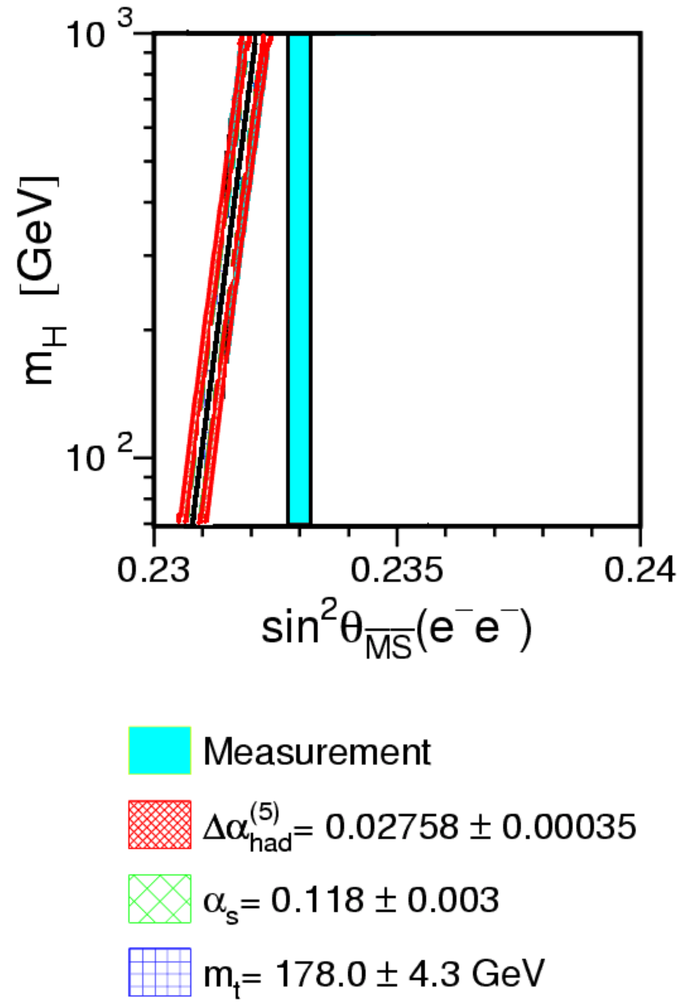
Similarly, if EW predictions of M_{Higgs} are not verified by LHC measurement… something very exciting is up

Møller sensitivity to M_{Higgs}



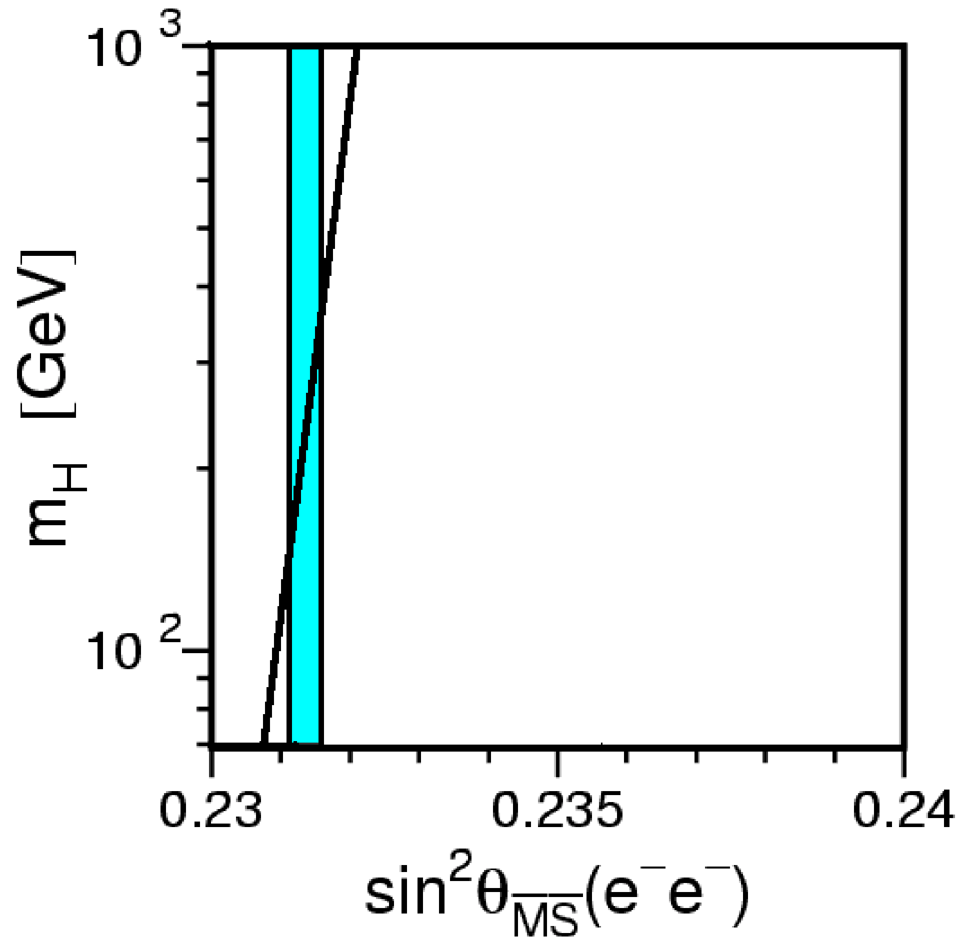
from E158
PRL 95(2005) 081601-1-5

Møller sensitivity to M_{Higgs}



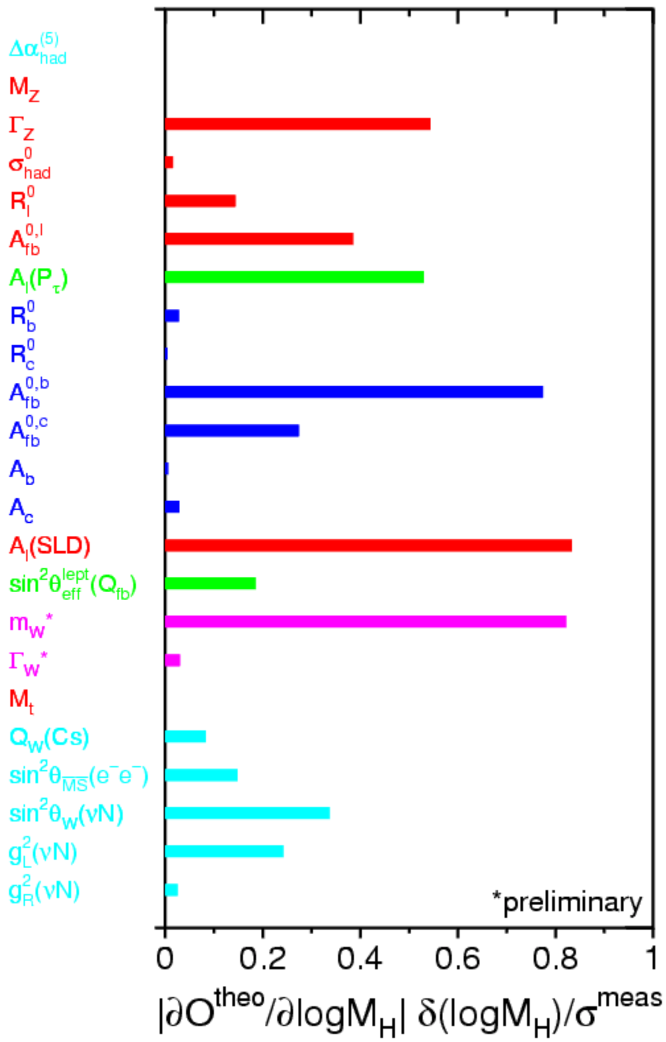
for projected error of 2.5E-4

Møller sensitivity to M_{Higgs}



for projected error of 2.5E-4 and no $\alpha_{had}^{(5)}(Mz)$ error

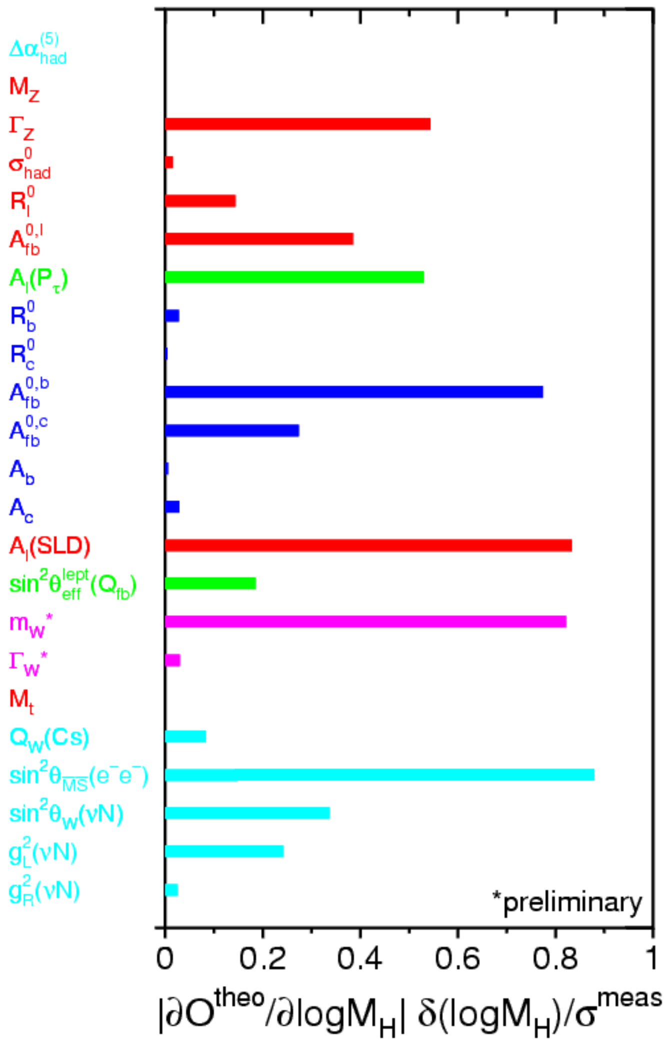
Møller sensitivity to M_{Higgs}



from E158
PRL 95(2005)
081601-1-5

UVic

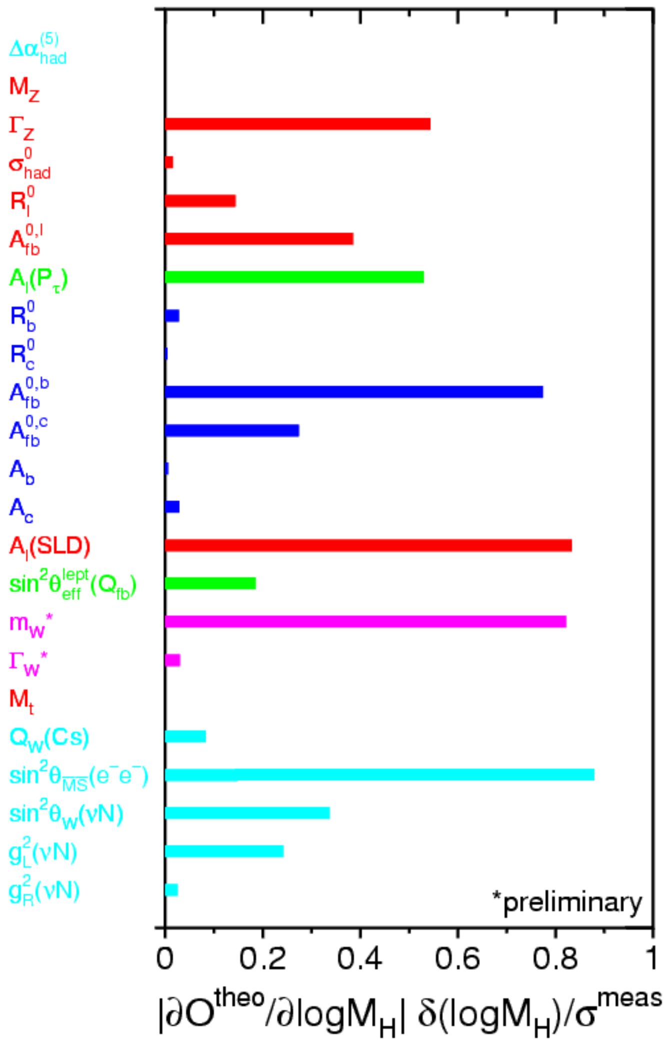
Møller sensitivity to M_{Higgs}



for projected error of 2.5E-4

UVic

Møller sensitivity to M_{Higgs}

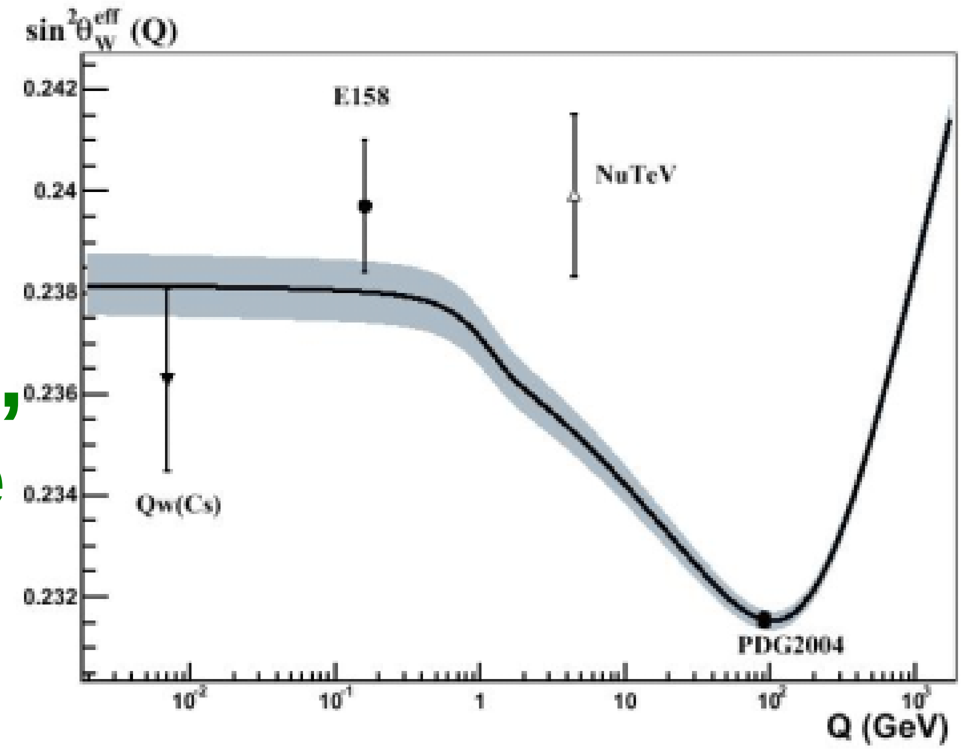


for projected error of 2.5E-4

but…new lepton measurements should be at least 0.00021 to have a big impact, beyond testing for running

Additional (obvious) note on complementarity Møller and High Energy Measurements of $\sin^2\theta_W$

As experimentalists we want to verify the running as precisely as possible, new physics could lie in failure of this running



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Summary

- Z^0-pole measurements from LEP and SLC provide the highest precision measurements of $\sin^2\theta_W$ but still make one uncomfortable:

  Success of predicting top mass; yet there is a chance that the $A_{FB}^{0,b}$ is telling us something about new physics
- New precision measurements in leptonic-hadronic couplings will come with A_{FB} in Drell-Yan at the LHC
- Additional precision measurement in purely leptonic couplings will be very useful to reinforce the LEP and SLC leptonic asymmetry data.

Summary

- Additionally, very high energy LHC asymmetries and c Møller measurements complementary to investigate running of a possible new effect
- Want to confront Higgs discovery at LHC with highest precision EW data possible: is it SM Higgs?
- LHC expected to give higher precision

  top and W masses
- Much more precise $\sin^2\theta_W$ would be very useful

  to help sort out what new physics might be at the LHC (but need improved $\Delta\alpha^{(5)}_{had}(Mz)$ to get there!)

Additional Slides

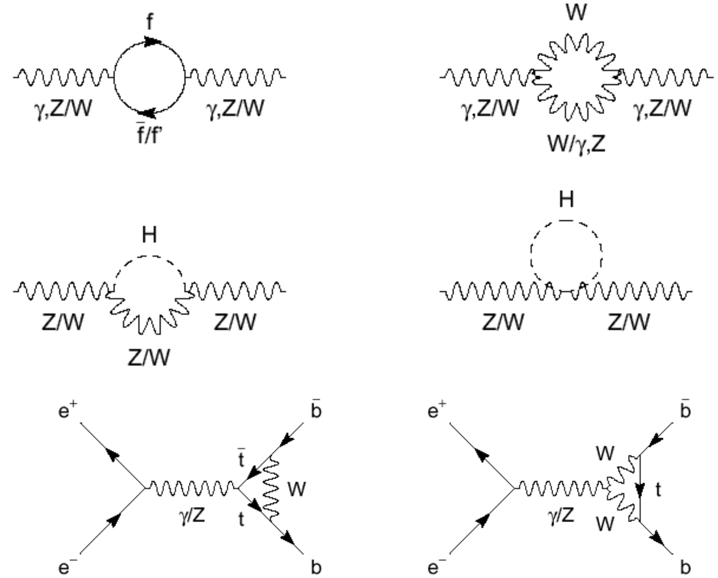
$$G_F = \frac{\pi\alpha}{\sqrt{2} m_W^2 \sin^2 \theta_W^{tree}}$$

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W^{tree}}$$ determined by Higgs structure (e.g.=1 if only Higgs doublets)

$$g_L^{tree} = \sqrt{\rho_0}\,(\mathrm{T_3^f} - \mathrm{Q_f} \sin^2\theta_W^{tree})$$
$$g_R^{tree} = -\sqrt{\rho_0}\,\mathrm{Q_f} \sin^2\theta_W^{tree}$$

or equivalently

$$g_V^{tree} = g_L^{tree} + g_R^{tree} = \sqrt{\rho_0}\,(\mathrm{T_3^f} - 2\mathrm{Q_f} \sin^2\theta_W^{tree})$$
$$g_A^{tree} = g_L^{tree} - g_R^{tree} = g_R^{tree} = \sqrt{\rho_0}\,\mathrm{T_3^f}$$



Modified by radiative corrections to propagators and vertices.
In 'on-shell' renormalization scheme, keep form of

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$$

and use this to define the on-shell EW mixing angle, θ_W, to all orders in terms of W and Z masses.

Bulk of corrections to the couplings at the Z-pole absorbed into complex form-factors: R_f for overall scale and K_f for the on-shell EW mixing angle, these give complex effective couplings:

$$\mathsf{G}_{Vf} = \sqrt{\mathsf{R}_f}\,(T_3^f - 2Q_f\,\mathsf{K}_f\,\sin^2\theta_W)$$

$$\mathsf{G}_{Af} = \sqrt{\mathsf{R}_f}\,T_3^f$$

In terms of the real parts

$$\rho_f \equiv RE(\mathsf{R}_f) = 1 + \Delta\rho_{se} + \Delta\rho_f$$

$$\kappa_f \equiv RE(\mathsf{K}_f) = 1 + \Delta\kappa_{se} + \Delta\kappa_f$$

$\Delta\rho_{se}$, $\Delta\kappa_{se}$ ↓ propagator self energy

$\Delta\rho_f$, $\Delta\kappa_f$ ↓ flavour-dependet vertex correction

The effective EW mixing angle and real effective couplings are defined as:

$$\sin^2\theta_{eff}^f \equiv \kappa_f \sin^2\theta_W$$

$$g_{Vf} \equiv \sqrt{\rho_f}\,(T_3^f - 2Q_f \sin^2\theta_{eff}^f)$$

$$g_{Af} \equiv \sqrt{\rho_f}\, T_3^f$$

So that:

$$\frac{g_{Vf}}{g_{Af}} = RE\left(\frac{G_{Vf}}{G_{Af}}\right) = 1 - 4|Q_f|\,\sin^2\theta_{eff}^f$$

For $m_H \gg m_W$ the leading order terms are:

$$\Delta\rho_{se} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots\right]$$

$$\Delta\kappa_{se} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2}\frac{\cos^2\theta_W}{\sin^2\theta_W} - \frac{9}{10}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots\right]$$

The flavour dependent terms are small except for b-quarks.

The form of the SM relation is preserved:

$$\cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha(0)}{\sqrt{2}m_Z^2 G_F}\frac{1}{1-\Delta r}$$

$$\cos^2\theta_{eff}^f \sin^2\theta_{eff}^f = \frac{\pi\alpha(0)}{\sqrt{2}m_Z^2 G_F}\frac{1}{1-\Delta r^f}$$

$$\Delta r = \Delta\alpha + \Delta r_w$$

$$\Delta r^f = \Delta\alpha + \Delta r_W^f$$

$$\Delta\alpha(s) = \Delta\alpha_{e\mu\tau}(s) + \Delta\alpha_{top}(s) + \Delta\alpha_{had}^{(5)}(s)$$

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

$$\Delta r_W^f = -\Delta\rho + \ldots$$

$$\Delta r_w = -\frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + \ldots$$

often used to express the W mass in terms of more precisely determined parameters:

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\pi\alpha}{\sqrt{2}G_F m_Z^2}\frac{1}{1-\Delta r}}\right)$$

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