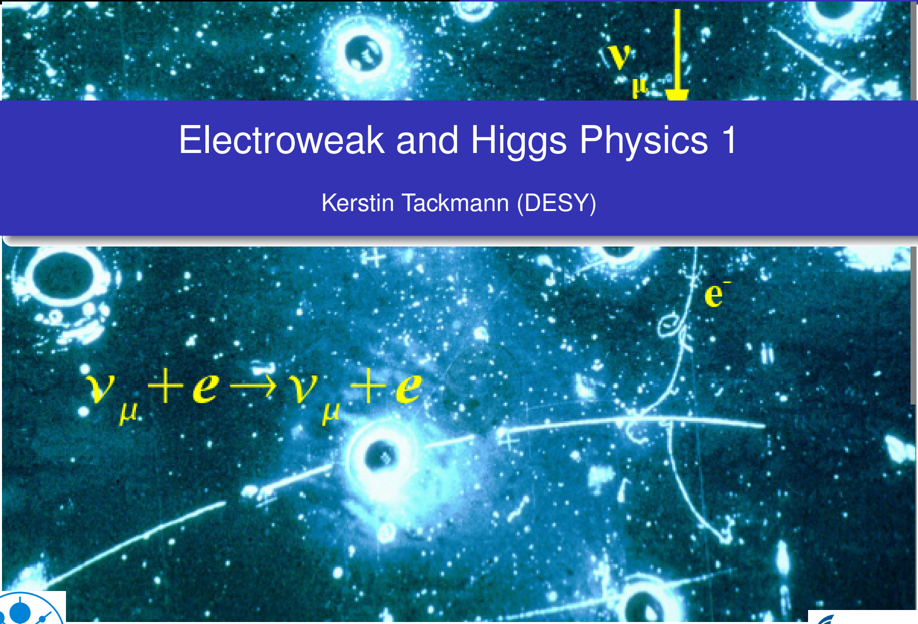
Electroweak and Higgs Physics 1

Kerstin Tackmann (DESY)



DESY Summer Student Program – August 7, 2013

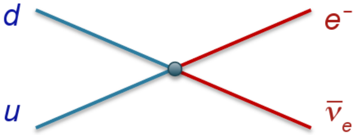
Electroweak and Higgs physics

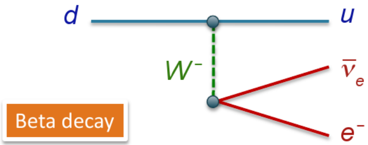
- Theory already covered last week by Jürgen Reuter
- Here: focus on those things not covered before and experimental aspects, with a few reminders
- Today's lecture: Mostly electroweak physics
- Tomorrow's lecture: Mostly Higgs physics

Many thanks to Marcel Stanitzki and Andreas Höcker!

Weak currents

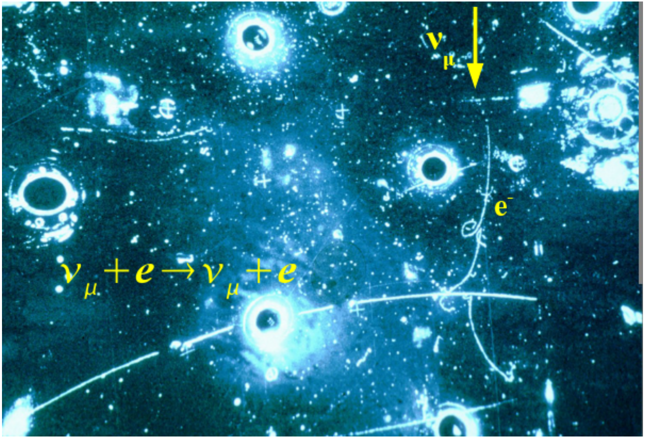
- To decribe β decay $n \to pe^-\bar{\nu}_e$:
  Fermi introduced 4point interaction
- Coupling constant G_F well-measured from μ lifetime:
  $G_F = 1.6637 \times 10^{-5}\,\mathrm{GeV}^{-2}$
- Ultraviolett divergences → Fermi theory only valid at low energies
- Solved by introduction of spin-1 boson: $W^\pm$
- 1967: Unification of electromagnetic and weak interaction: electroweak interaction with 3 massive ($W^\pm$, Z) and one massless (γ) bosons



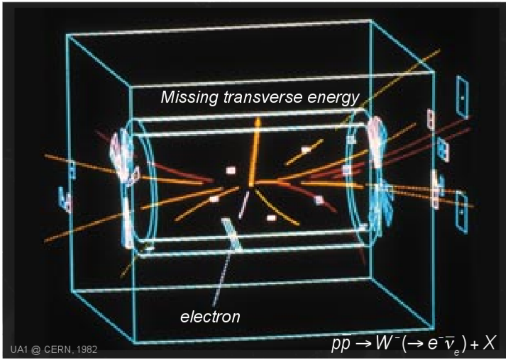


Discovery of the neutral current

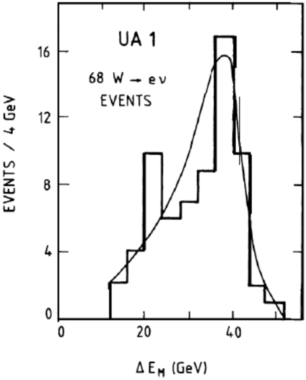
Neutral current discovered in 1973 with Gargamelle at CERN by observing $\nu_\mu e \to \nu_\mu e$



W and Z discoveries at SppS in 1983



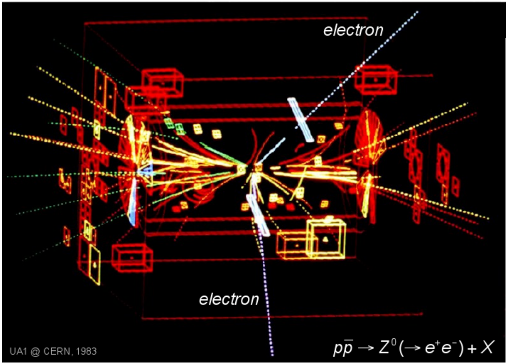
Missing transverse energy in events with $E_e > 15$ GeV

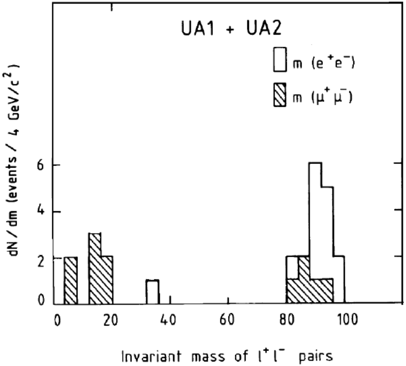


$$m_W = (80.9 \pm 1.5 \pm 2.4)\ \mathrm{GeV}$$

C. Rubbia, Nobel Lecture, 1984

W and Z discoveries at SppS in 1983





$$m_Z = (95.1 \pm 2.5)\,\mathrm{GeV}$$

C. Rubbia, Nobel Lecture, 1984

Electroweak interactions

Remember from particle physics theory lecture

- Glashow, Salam and Weinberg unified electromagnetic and weak interactions to electroweak interaction
- Gauge fields are linear combinations of
  B^0 (U(1)$_Y$ weak hypercharge with coupling g'), and
  $W^{1,2,3}$ (SU(2)$_L$ weak isospin with coupling g)

$$W^{\pm} = \frac{1}{\sqrt{2}}(W^1 \mp iW^2)$$

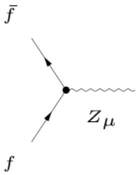
$$Z = \cos\theta_W W^3 - \sin\theta_W B^0$$

$$A = \sin\theta_W W^3 + \cos\theta_W B^0$$

- with the masses related (at tree level): $m_W = m_Z \cos\theta_W$
  and θ_W the weak mixing angle with

$$\sin\theta_W = \frac{g'}{\sqrt{g'^2 + g^2}}$$

Electroweak interactions



$$-i\frac{g}{2\cos\theta_W}\gamma_\mu\left[(I^3_f - 2\sin^2\theta_W Q_f) - \gamma^5 I^3_f\right] =$$
$$-i\frac{g}{2\cos\theta_W}\gamma_\mu\left[g^{(0)}_{V,f} - \gamma^5 g^{(0)}_{A,f}\right]$$

with g coupling of $SU(2)_L$, I^3_f third component of weak isospin, Q_f f charge

Vector and axial-vector couplings for $Z \to f\bar{f}$

$$g^{(0)}_{V,f} = g^{(0)}_{L,f} + g^{(0)}_{R,f} = I^3_f - 2\sin^2\theta_W Q_f$$
$$g^{(0)}_{A,f} = g^{(0)}_{L,f} - g^{(0)}_{R,f} = I^3_f$$

Remember projection operators $P_L = \frac{1}{2}(1-\gamma^5)$ and $P_R = \frac{1}{2}(1+\gamma^5)$

Electroweak unification: relation between weak and electromagnetic couplings:

$$G_F = \frac{\pi\alpha(0)}{\sqrt{2}(M^{(0)}_W)^2(1-(M^{(0)}_W)^2)/M^2_Z)}$$

Often choose as 3 free parameters (tree level): α, M_Z, G_F and then

$$M^2_W = \frac{M^2_Z}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha}{G_F M^2_Z}}\right)$$

Radiative corrections

Radiative corrections – modifying propagators and vertices

Parametrisation of radiative corrections: "electroweak form-factors": ρ, κ, Δr

- Modified ("effective") couplings at the *Z* pole:

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

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

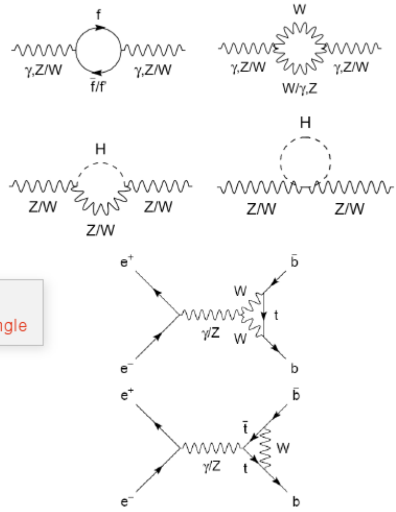
$$\sin^2\theta_{\mathrm{eff}}^f = \kappa_Z^f \sin^2\theta_W$$

ρ : overall scale

κ : on-shell mixing angle

- Modified *W* mass:

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



Radiative corrections

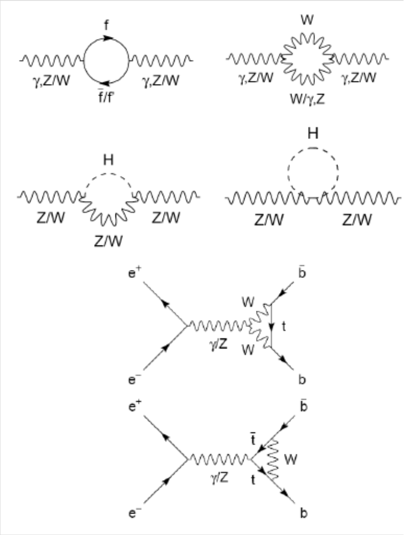
Radiative corrections – modifying propagators and vertices

Important consequences

→ All other SM parameters enter the calculations

- In particular corrections are ~m^2_{top} and ~$\ln(M_H)$
- 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**



Radiative corrections

Radiative corrections – modifying propagators and vertices

Leading order terms ($M_H \ll M_W$)

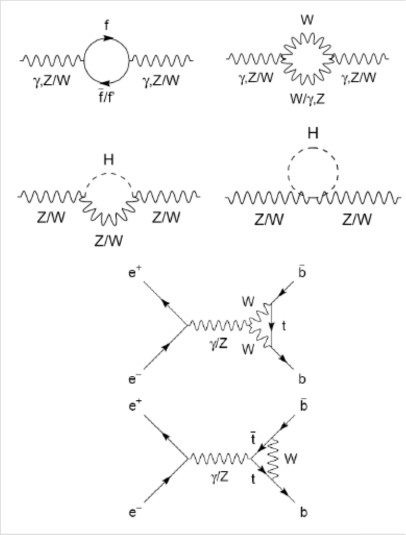
- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

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

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

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

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



Electroweak precision physics

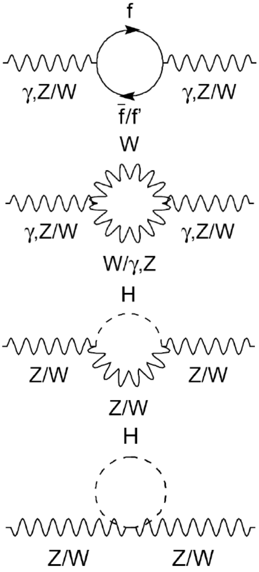
- Electroweak theory makes very distinct predictions, which can be tested by precision measurements performed by LEP, the Tevatron and also the LHC

- This also needs theoretical predictions with small and well-understood uncertainties → include higher-order corrections

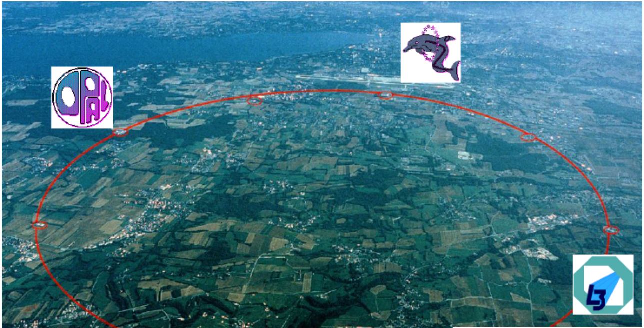
- Sensitivity to top quark and Higgs via radiative corrections

- Most important experimental input to a global fit
  - ⋆ $e^+e^- \to f\bar{f}$ measured at the Z-pole: Z mass and (partial) width(s), asymmetries (LEP and SLC)
  - ⋆ W mass and width (LEP and Tevatron)
  - ⋆ top mass (Tevatron)

→ This is the menu for today



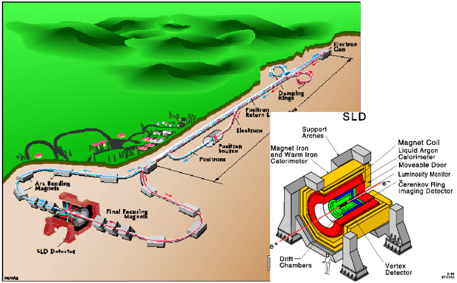
LEP and SLC



LEP-I (1989-1995)
$\sqrt{s} = \mathbf{91.2\,GeV}$

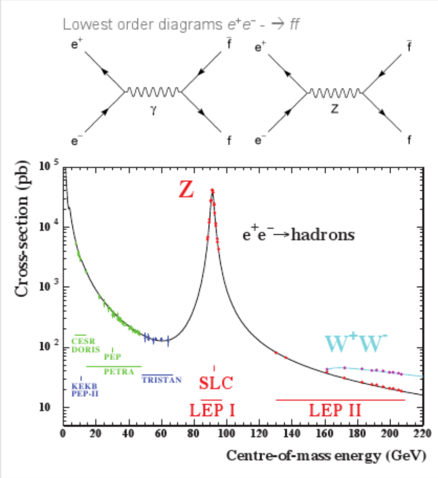
LEP-II (1996-2000)
$\sqrt{s} = \mathbf{160-209\,GeV}$

SLC (1989-1998)
$\sqrt{s} = \mathbf{91.2\,GeV}$



Measurements at the Z pole

Important experimental input to the fit: electroweak precision data measured at the Z^0-resonance



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

- 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)

Z-to-fermion vertex has vector and axialvector components → parity violation

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

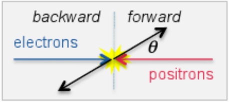
Neglects photon ISR & FSR, gluon FSR, fermion masses

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 $\cos\theta$ symmetric terms) expressed in Breit-Wigner form:

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

Corrected for
QED radiation

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

- 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: $\sigma^0{}_{\mathrm{had}}$
- Three leptonic ratios (use lepton-univ.): $R_\ell^0 = R_e^0 = \Gamma_{\mathrm{had}} / \Gamma_{ee} = R_\mu^0 = R_\tau^0$
- Hadronic width ratios: R_b^0, R_c^0

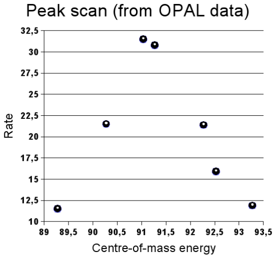
Taken from LEP:

- precise $\sqrt{s}$
- high statistics

Include also SLD:

- higher effi./purity for heavy quarks

Z mass and width: measurement



- Perform energy scan around Z peak
- Measure hadronic and leptonic Z decays

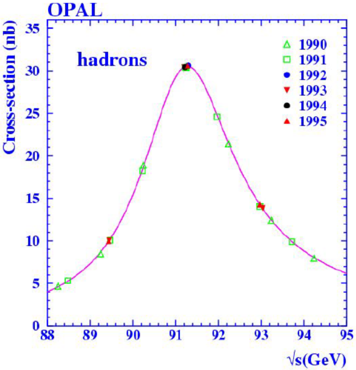
Obtain hadronic cross section as

$$\sigma_{\text{had}} = \frac{1}{L}\frac{1}{\epsilon}(N_{\text{had}} - N_{\text{bkgd}})$$

with ϵ and N_{bkgd} from simulation

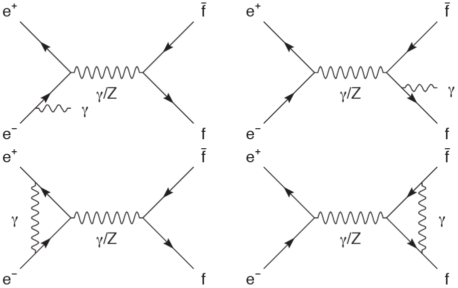
Trigger efficiency $> 99\%$

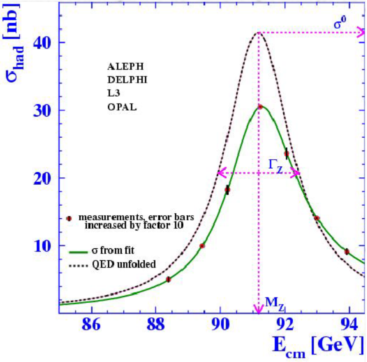
$$\sigma^Z_{f\bar{f}}(s) = \sigma^0_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + \frac{s^2}{m_Z^2}\Gamma_Z^2}$$



Z mass and width: radiative corrections

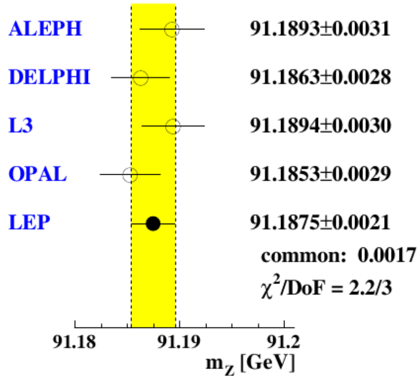
- Measured cross section is modified by initial and final state radiation
- Corrections can be large: QED corrections can be 30%
- Effects are corrected for by the experiments

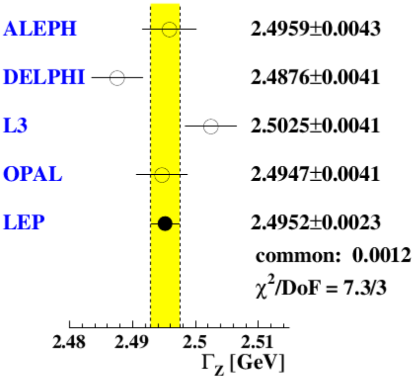




Z mass and width

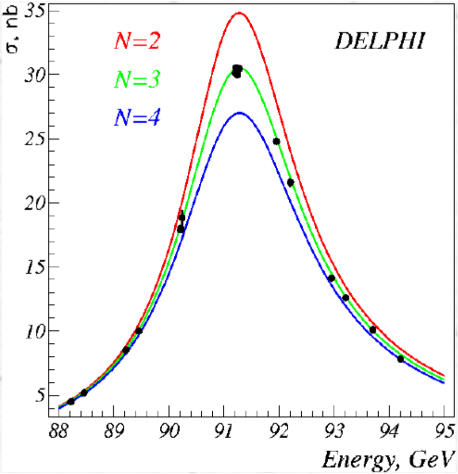
Z mass and width as measured by the LEP experiments





Z and the neutrinos

Number of light ($m_\nu < \frac{1}{2}m_Z$) neutrinos can be determined from the Z width



Use measured hadronic cross section

$$\sigma^0_{\mathrm{had}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\mathrm{had}}}{\Gamma_Z^2} \text{ and}$$

$$\Gamma_Z = \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{lep}} + \Gamma_{\mathrm{inv}}$$

$$\Gamma_{\mathrm{inv}} = n\Gamma_\nu$$

$$n = 2.984 \pm 0.008$$

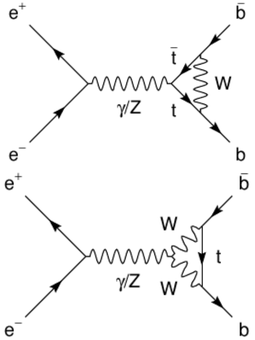
(LEP+SLC combined result)

Limit before LEP: 4-16 types of neutrinos allowed

R_b

Hadronic width into b-quarks: $R_b = \Gamma_b / \Gamma_{\mathrm{had}}$

- Significant enhancement of R_b from large mass of top quark m_t
- m_t unknown at the time of this measurement! top had not yet been seen in any experiment
- If there was no top quark, Γ_b would be small



How to identify b-jets?

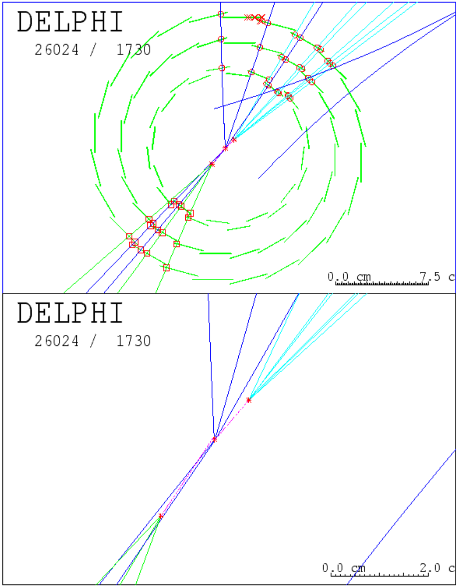
- b quark decays weakly, with long lifetime ($\tau_b = 1.6\,\mathrm{ps}$) due to V_{cb} being small

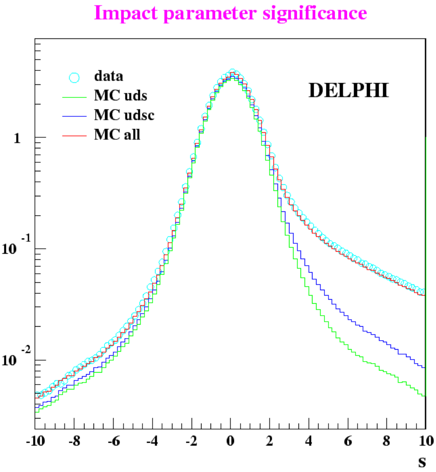
→ Measureable decay length ($\sim 3\,\mathrm{mm}$ for production at the Z peak)

→ Tracks appear to miss the reconstructed primary vertex

- Impact parameter significance measures significance of distance of closest approach of reconstructed track to interaction point

Identification of b-jets at DELPHI



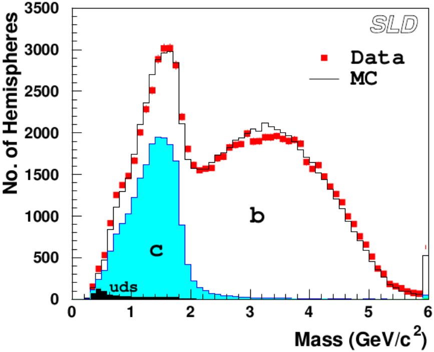


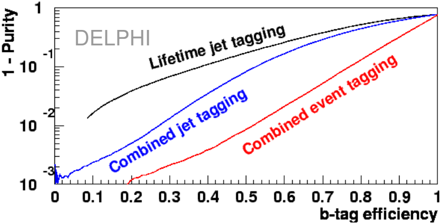
Improved b-jet identification

One can do better:
Combine information

- Impact parameter
- Secondary vertex mass
- Presence of lepton
  - ⋆ Lepton charge carries information about b vs $\bar{b}$
- Secondary vertex charge
- Secondary vertex p_T

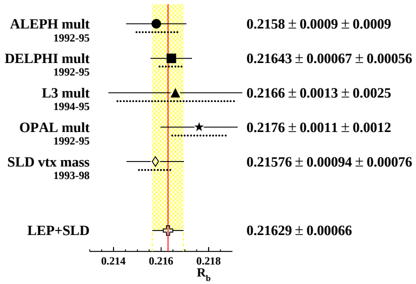
Best b-tagging performance at SLD due to highly granular Si Pixel detector



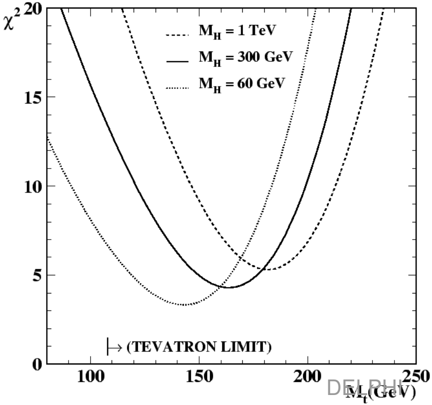


R_b results

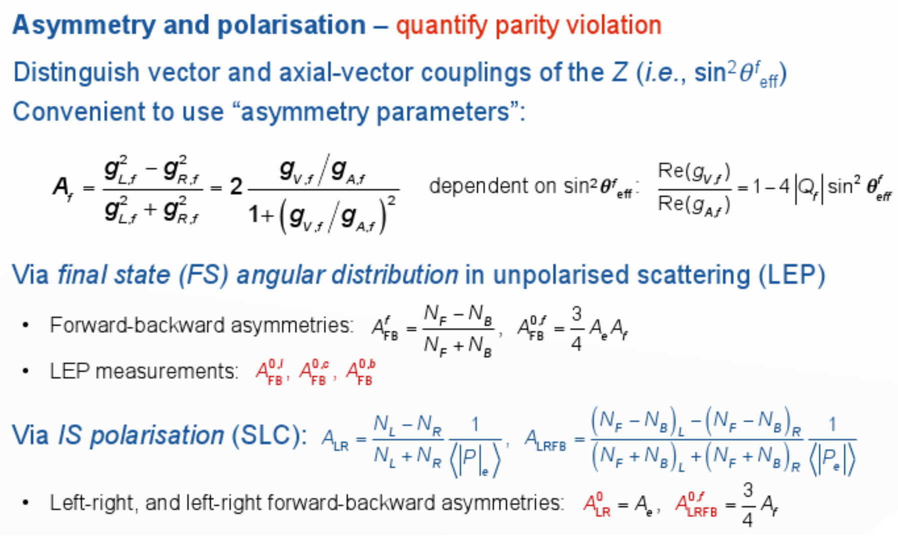
Results from LEP and SLD



Can already learn top is heavy before direct evidence for top from Tevatron



Measurements at the Z pole



Asymmetry and polarisation – quantify parity violation

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

Convenient to use “asymmetry parameters”:

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

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

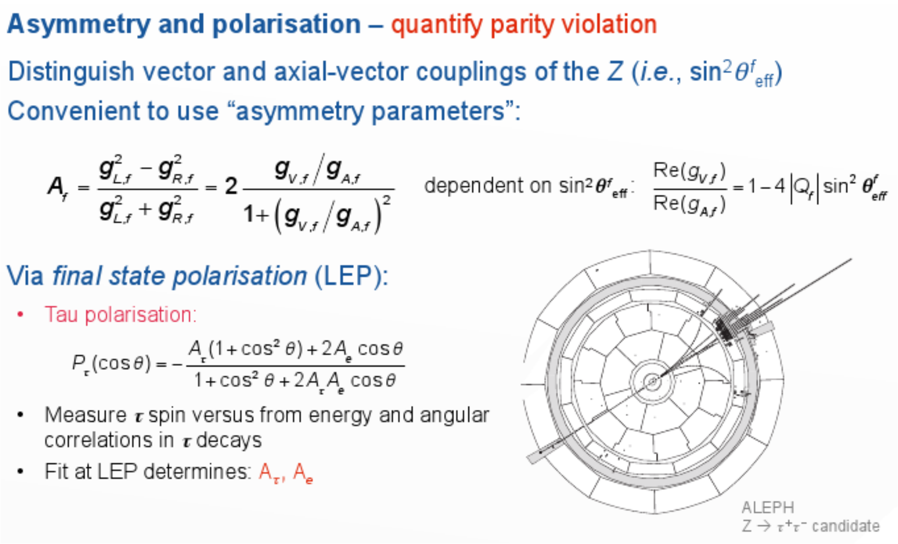
Via *final state (FS) angular distribution* in unpolarised scattering (LEP)

- Forward-backward asymmetries: $A^f_{\text{FB}} = \frac{N_F - N_B}{N_F + N_B}$, $A^{0,f}_{\text{FB}} = \frac{3}{4}A_e A_f$
- 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



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

Via *final state polarisation* (LEP):

- Tau polarisation:

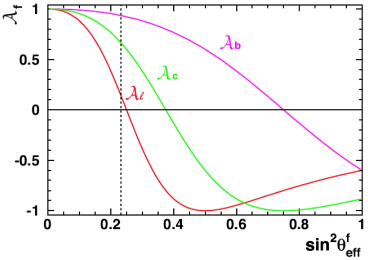
$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta)+2A_e\cos\theta}{1+\cos^2\theta+2A_\tau A_e\cos\theta}$$

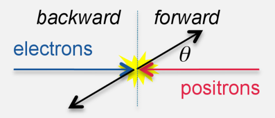
- Measure τ spin versus from energy and angular correlations in τ decays
- Fit at LEP determines: A_τ, A_e

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

Forward-backward asymmetries

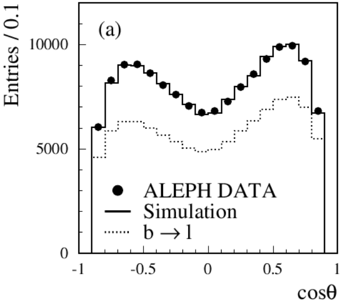
A_ℓ particularly sensitive to $\sin^2\theta_W^{\rm eff}$

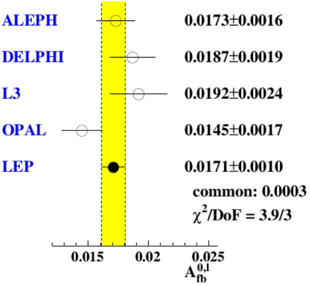




$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- A_{FB} measured from from event counting or fitting the $\cos\theta$ distribution



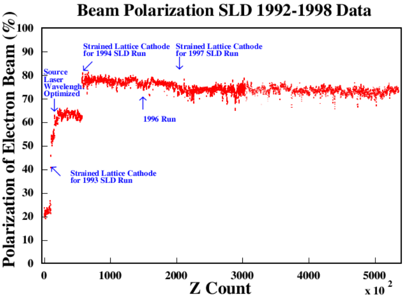


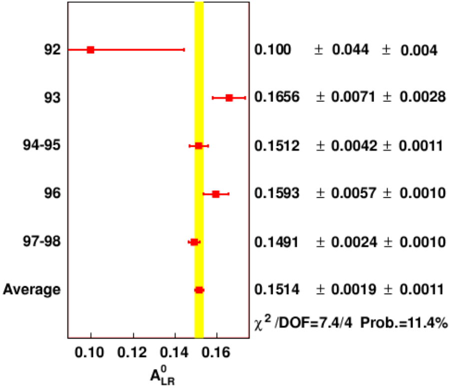
Left-right asymmetries at SLC

$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} \frac{1}{\langle |P|_e \rangle}$$

- Single most sensitive to $\sin^2 \theta_W^{\mathrm{eff}}$
- Do not use electron final state to eliminate t-channel process

e^--beam polarization at SLC $\sim 75\%$



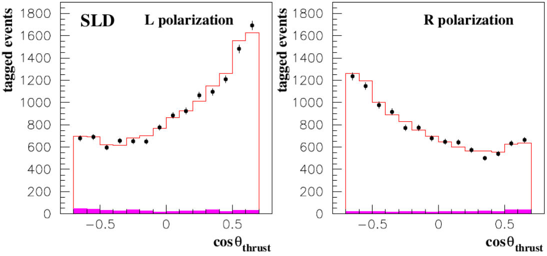


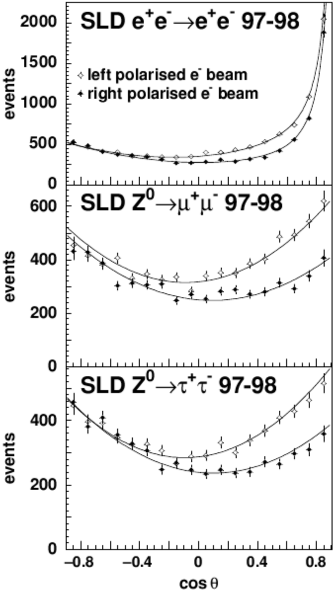
$$\sin^2 \theta_W^{\mathrm{eff}} = 0.23097 \pm 0.00027$$

Left-right forward-backward asymmetries at SLC

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \frac{1}{<\mathcal{P}_e>}$$

- A_f determined with statistical precision equivalent to unpolarized forward-backward asymmetry with a 25 times larger data sample (with 75% e^--beam polarization)





W mass at Tevatron

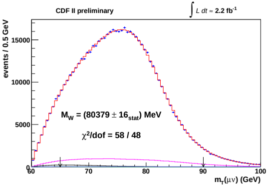
W mass measured at Tevatron with high precision

- Leptonic decays of W: $W \to e\nu$, $W \to \mu\nu$
- Template fits to transverse mass m_T, lepton p_T^ℓ and neutrino p_T^ν (from transverse energy) distributions with

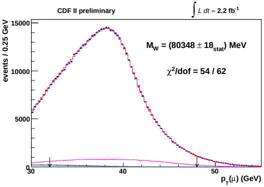
$$m_T = \sqrt{2p_T^\ell p_T^\nu(1 - \cos(\phi^\ell - \phi^\nu))}$$

  - ⋆ Templates for 1600 between $m_W = 80$ and $81\,\mathrm{GeV}$
  - ⋆ Uncertainties dominated by knowledge of lepton and recoil energy scale and parton distribution functions

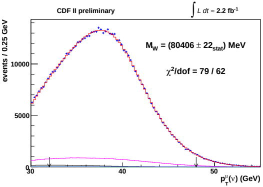
m_T



p_T^ℓ



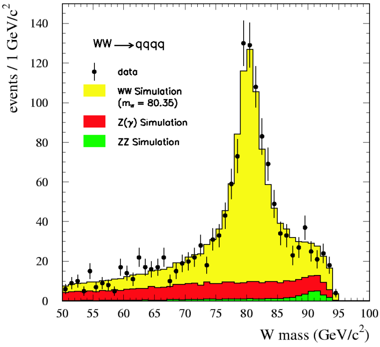
p_T^ν

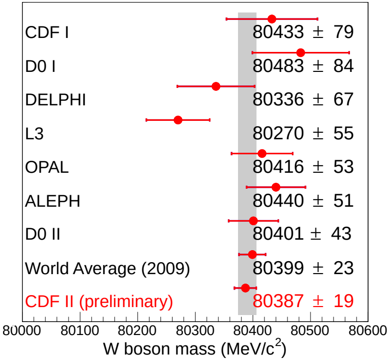


W mass at LEP-II (and Tevatron)

W mass also measured by LEP-II in $e^+e^- \to W^+W^-$

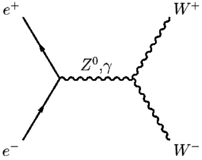
- $e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$ events above threshold
  - ⋆ Kinematic contraints: all momenta sum up to 0 and two $q\bar{q}$ pairs should have equal mass
- Threshold scan using about $10\,\mathrm{pb}^{-1}$ per experiment recorded around the WW threshold



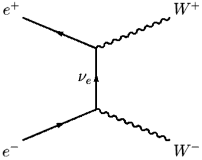


$e^+e^- \rightarrow W^+W^-$

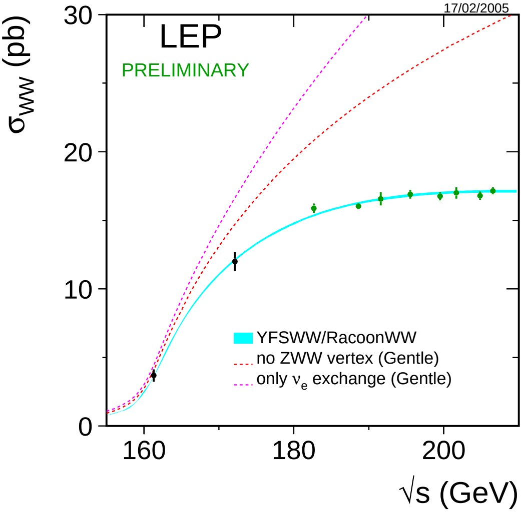
Trilinear gauge couplings, e.g. ZWW vertex predicted by Glashow-Salam-Weinberg...



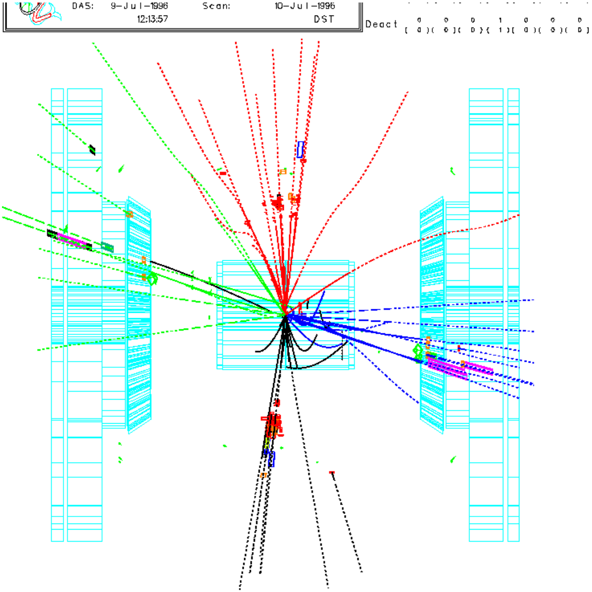
...in addition to other WW production...



...and seen at LEP



First WW pair seen by DELPHI



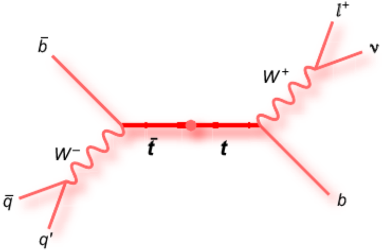
4-jet event

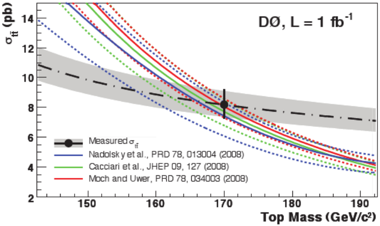
$$e^+e^- \to W^+W^-$$
$$\to q\bar{q}q\bar{q}$$

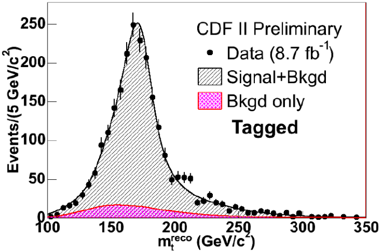
top mass at Tevatron

top almost always decays as $t \to Wb$

- Mass measured in top decays to dilepton (4%), lepton+jets (30%) and fully hadronic (46%)
- Analysis heavily relies on identification of b-jets (b-tagging)
- Template analysis finding m_t and jet-energy-scale simultaneously
- Complementary method: Extract m_t from measured $t\bar{t}$ cross section







Global electroweak fit

Many different quanities measured

- Z pole, cross sections and branching ratios M_Z, Γ_Z, σ^0_{had}, R^0_ℓ, R^0_b, R^0_c
- Asymmetries at the Z pole $A^{0,\ell}_{FB}$, $A^{0,b}_{FB}$, $A^{0,c}_{FB}$, A_ℓ, A_b, A_c, $sin^2\theta^{\text{eff}}_W$
- And additional observables M_W, Γ_W, m_t

...some measurements were briefly described here.

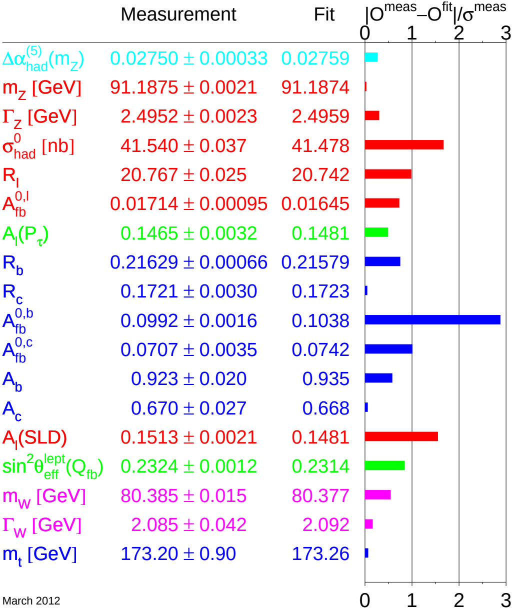
These (and a few others) are combined in a global fit

- Global fits to electroweak measurements have a long history:
  - ZFITTER (D. Bardinet et. al.)
  - TOPAZ0 (G. Passarino et et. al.)
  - LEP Electroweak Working Group (M. Grünewald et. al.)
  - Gfitter (M. Baak et. al.)
  - GAPP (J. Erler)

Global electroweak fit

Inspect pulls ($\frac{|O^{meas} - O^{fit}|}{\sigma^{meas}}$)
to judge goodness-of-fit

- No pull exceeds 3σ
  - ⋆ 0.8 measurements outside of 2σ expected
- $A_{FB}^{0,b}$ shows largest pull value

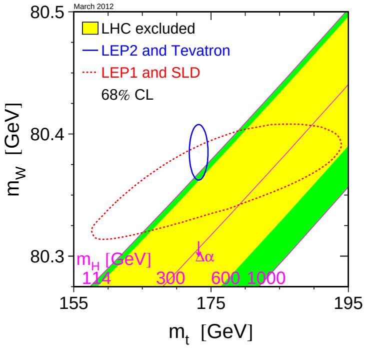


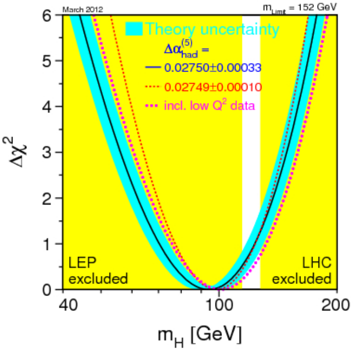
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

March 2012

Constraining the Higgs mass

- m_W and m_t constrained from measurements at the Z pole
- Good agreement between indirect and direct measurements of m_W and m_t
- Direct measurements agree well with light Higgs

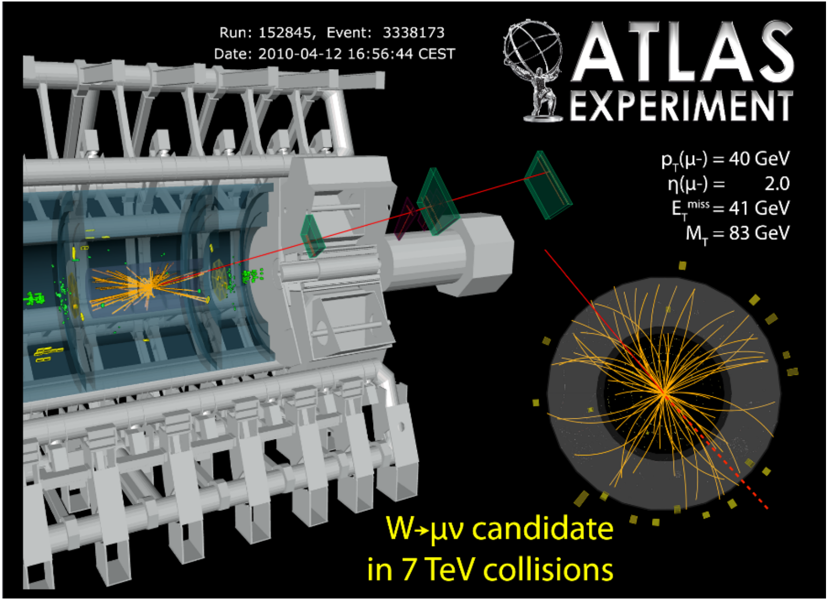




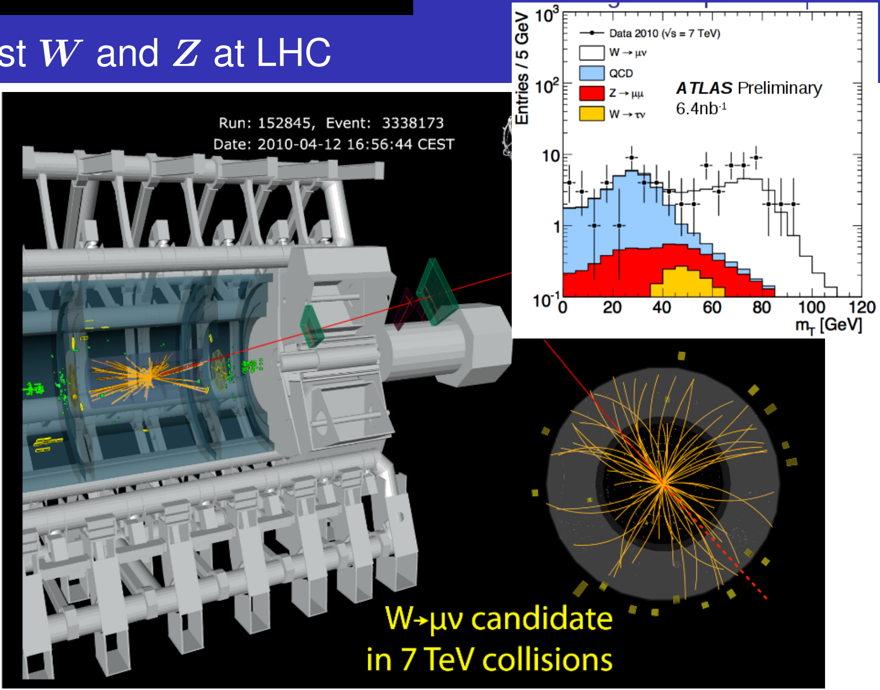
- Indirect contraints on Higgs mass $m_H < 152\,\mathrm{GeV}$

→ Direct searches: tomorrow's lecture

First W and Z at LHC

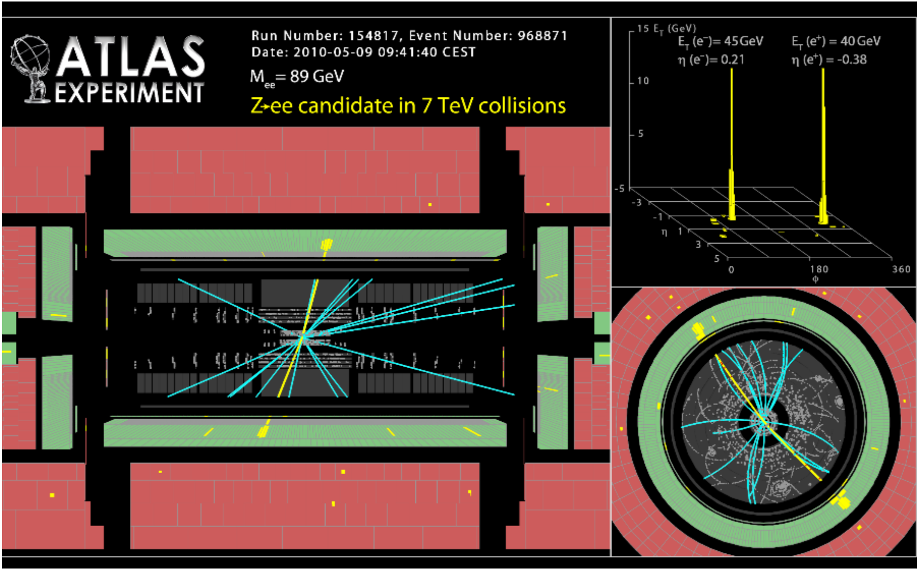


First W and Z at LHC

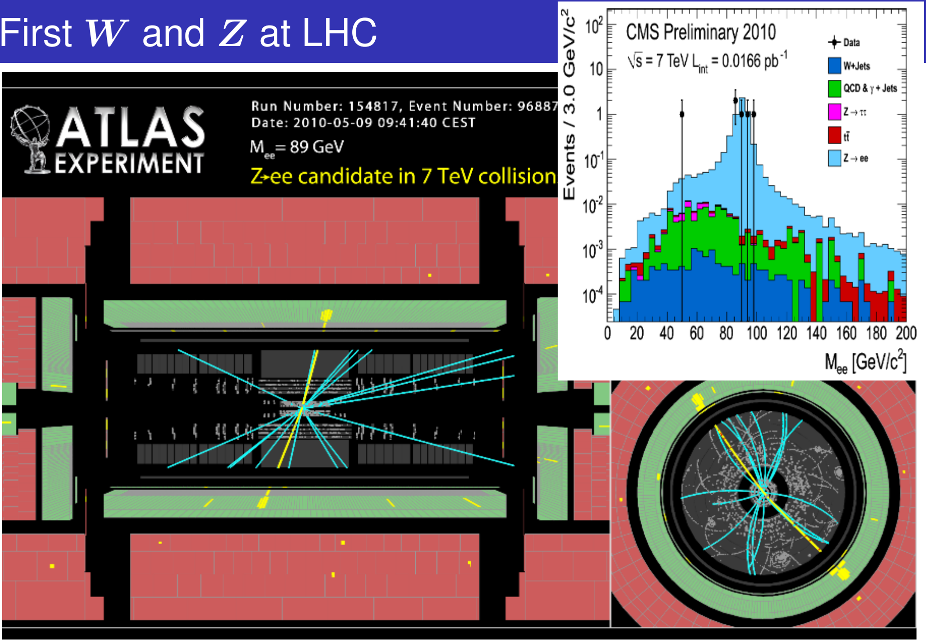


W→μν candidate
in 7 TeV collisions

First W and Z at LHC



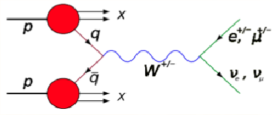
First W and Z at LHC

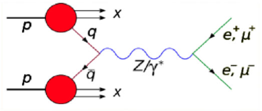


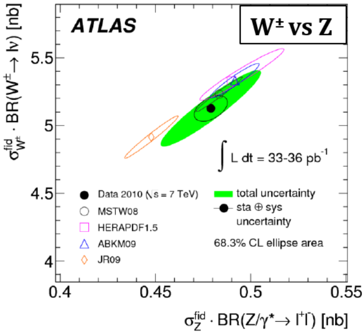
W and Z at LHC

W and Z produced copiously at LHC

- Leptonic decays have clean signatures, good tool for understanding the detectors
- Precision test of the SM
- Important backgrounds for Higgs and New Physics searches





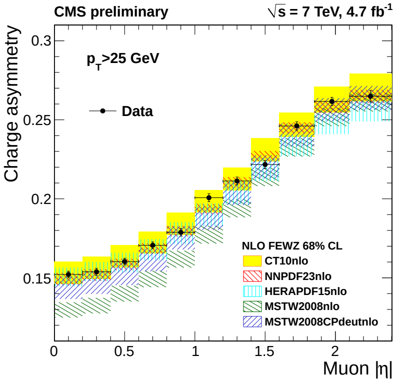


- Inclusive production cross sections for W and Z
- Test of higher-order QCD calculations...
- ...and of parton density functions

W and Z at LHC

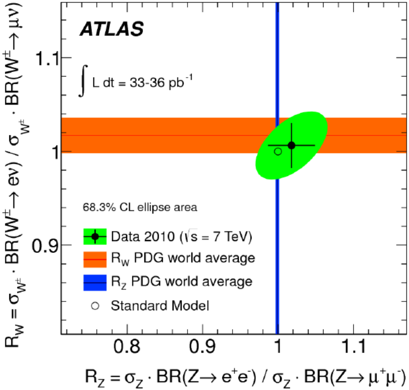
Many more aspects can be tested...

...charge asymmetry in W production (→ PDFs)...



Protons have uud as valence quarks and prefer W^+ production

...lepton universality in decays to electrons and muons...



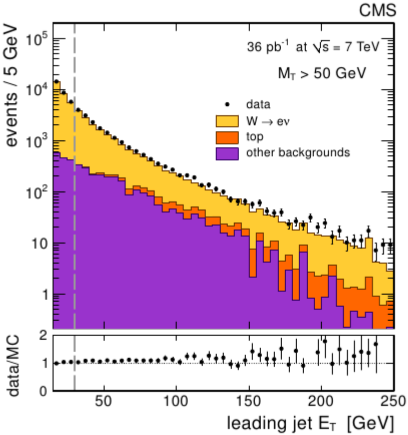
Good agreement with (more precise) world average

W/Z+jets

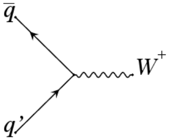
W+jets is important background to many new physics searches

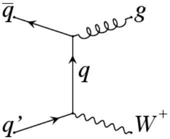
- Higgs searches are one of them

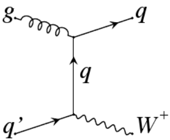
Highest-E_T jet spectrum in $W \rightarrow e\nu$

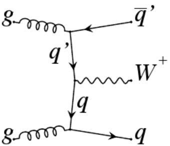


Production of $W + 0, 1, 2$ jets







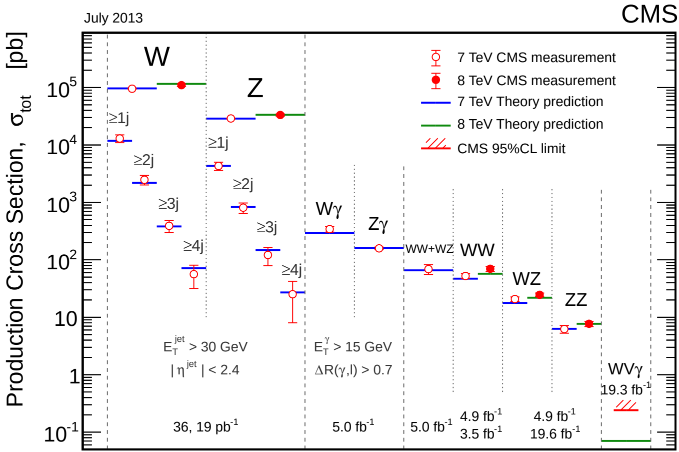


Every additional jet suppressed by $\sim \alpha_s$

Precision tests for perturbative QCD (pQCD)

Electroweak measurements at LHC

Understanding many aspects of electroweak physics, and also important background processes for Higgs (and other) searches at LHC



JHEP 10 132 (2011)
JHEP 01 010 (2012)
SMP-12-011 (W/Z 8 TeV)

EWK-11-009

EPJC C13 2283 (2013) (WV)
SMP-12-006 (WZ), 12-005 (WW7), 13-005(ZZ8)
JHEP 1301 063 (2013) (ZZ7), PLB 721 190 (2013) (WW8)

SMP-013-009

Good agreement between measurements and predictions!

Summary electroweak physics

- Electroweak precision measurements at the Z pole by LEP and SLC offer stringent test of SM and constrain other SM parameters
  - Masses of W, top, Higgs
  - They also tell us there are 3 generations of (light) neutrinos
- Very good agreement with SM predictions observed
- Tomorrow we will turn to direct searches for the Higgs at LEP, Tevatron and the LHC
- W and Z will also play an important role there...