

## Outline

- Relativistic Kinematics
  - ▶ (4-momentum)2 invariance, invariant mass
  - ▶ Hypothesis testing, production thresholds
  - ▶ Cross-sections, flux and luminosity, accelerators
  - ▶ Particle lifetime, decay length, width
- Classification of particles
  - ▶ Fermions and bosons
  - ▶ Leptons, hadrons, quarks
  - ▶ Mesons, baryons
- Quark Model
  - ▶ Meson and baryon multiplets
  - ▶ Isospin, strangeness, c, b, t quarks
- Particle Interactions
  - ▶ Colour charge, QCD, gluons, fragmentation, running couplings
  - ▶ Strong and weak decays, conservation rules
  - ▶ Virtual particles and range of forces
  - ▶ Parity, charge conjugation, CP
  - ▶ Weak decays of quarks
  - ▶ Charmonium and upsilon systems
- Electroweak Interactions
  - ▶ Charged and neutral currents (Z)
  - o Perkins, p317-318;
  - o Griffiths, pp. 72-74.
- LHC Experiments' Results
- Future - introduction to accelerator physics ☺

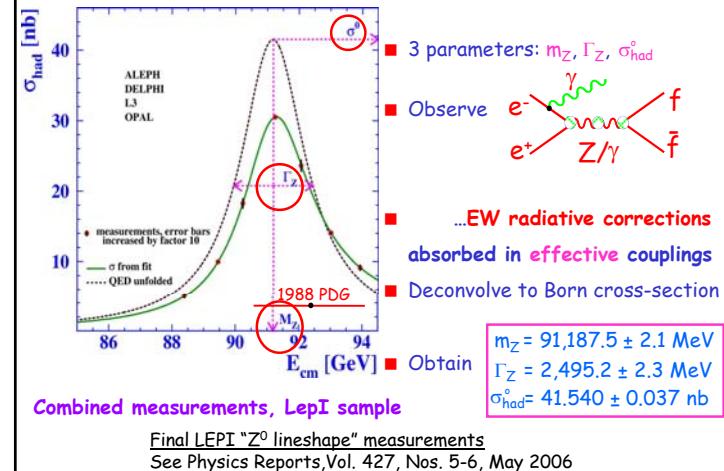
Today

Previous lecture

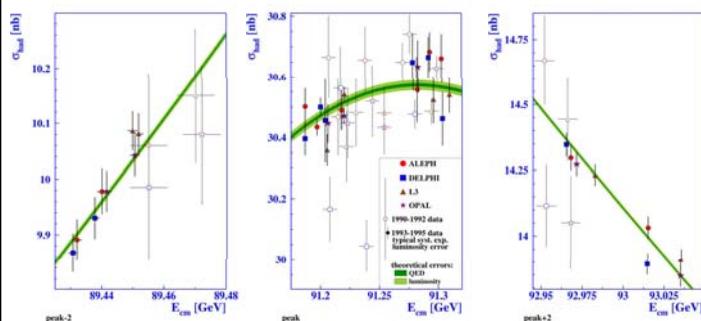
Lecture 21 (4 slides/page) - Z couplings, decay widths, couplings, Higgs  
o Martin and Shaw, pp. 226-229

Lecture 20 (4 slides/page) Weak neutral currents (Z) and experiments  
o Perkins, p317-318;  
o Griffiths, pp. 72-74.

## LEP Lineshape: 1989+...final results



## Details of LepI Cross-Section Data



All 4 LEP experiments and years of LepI

## No. of Neutrino Generations

- "Invisible width",  $\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - 3 \Gamma_\ell$
- No. of generations =  $\Gamma_{\text{inv}} / \Gamma_v^{\text{SM}}$    SM:  $\Gamma_v^{\text{SM}} = \frac{G_F m_Z^3}{6\pi\sqrt{2}} (c_v^2 + c_a^2) \approx 166 \text{ MeV}$   
► Measure  $\Gamma_{\text{inv}}$
- $c_v + c_a$  are vector and axial vector couplings of neutrino to Z
- Direct: measure  $\sigma(e^+e^- \rightarrow v\bar{v}\gamma)$  soft γ + nothing else...challenging!
- Indirect: measure  $m_Z, \Gamma_Z, R_\ell, \sigma_{\text{had}}^o$ 

$$\sigma_{\text{had}}^o \equiv \frac{12\pi\Gamma_e\Gamma_{\text{had}}}{(m_Z\Gamma_Z)^2}$$

$$\Gamma_{\text{inv}} / \Gamma_v^{\text{SM}} = \left( \frac{12\pi}{m_Z^2 \sigma_{\text{had}}^o} \right)^{\frac{1}{2}} - R_\ell - 3$$

$$\Rightarrow N_\nu = 2.9841 \pm 0.0083 \quad \text{for } m_\nu \leq \frac{1}{2}m_Z \sim 45 \text{ GeV}$$
- For  $N_\nu = 3$ , width from new Z decay modes =  $-2.7 \pm 1.6 \text{ MeV}$
- Still room for heavy or sterile neutrinos

## P and T transformations

Observable	Parity transform
Position, $\mathbf{r}$	$-\mathbf{r}$ (vector)
Momentum, $\mathbf{p}$	$-\mathbf{p}$ (vector)
Spin, $\sigma$	$\sigma$ (axial vector)
Longitudinal polarisation, $\sigma \cdot \mathbf{p}$	$-\sigma \cdot \mathbf{p}$ (pseudoscalar)
Electric field, $\mathbf{E}$	$-\mathbf{E}$ (vector)
Magnetic field, $\mathbf{B}$	$\mathbf{B}$ (axial vector)
Magnetic dipole moment, $\sigma \cdot \mathbf{B}$	$\sigma \cdot \mathbf{B}$ (scalar)
Electric dipole moment, $\sigma \cdot \mathbf{E}$	$-\sigma \cdot \mathbf{E}$ (pseudoscalar)

## Z couplings to fermions

fermion	$c_v$	$c_a$
$\nu_e, \nu_\mu, \nu_\tau$	$\frac{1}{2}$	$\frac{1}{2}$
$e^-, \mu^-, \tau^-$	$-\frac{1}{2} + 2\sin^2\theta_W$	$-\frac{1}{2}$
$u, c, \bar{t}$	$\frac{1}{2} - (4/3)\sin^2\theta_W$	$\frac{1}{2}$
$d, s, b$	$-\frac{1}{2} + (2/3)\sin^2\theta_W$	$-\frac{1}{2}$

$$c_v/c_a = 1 - 4Q_f \sin^2\theta_W$$

where  $Q_f$  is fermion e.m. charge (units of  $|e|$ ), for all fermion species

$\theta_W$  is the “weak mixing angle” (determined experimentally)

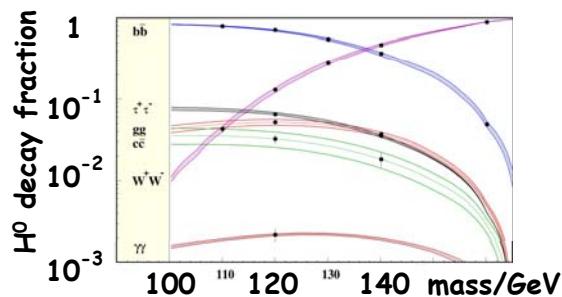
Connects weak and e.m. charges by  $e=g \sin\theta_W$

Measured value  $\sin^2\theta_W=0.232$

At “lowest order”,  $M_w = M_Z \cos\theta_W$

## Higgs in $e^+e^-$ collisions

- Multi-jets: Higgs spectroscopy, WW/ZZ, tt decays



No ambiguity in predictions.

Precise measurement only possible at lepton colliders.

## e.g. SM Combined Fits to Data



Consistency of data with SM, illustrated by “pull” values i.e. for each observable,  $O_i$ ,  $|O_i^{\text{meas}} - O_i^{\text{fit}}| / \text{error}(O_i)$

See LEP Electroweak Working Group

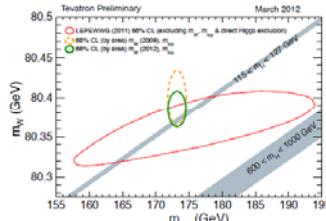
<http://lepwwg.web.cern.ch/LEPEWWG/>

Now  $m_W$  is the most constraining variable in the indirect limit to  $m_H$

With  $M_W = 80385 \pm 15$  MeV

$m_H = 94^{+29}_{-34}$  GeV  
 $m_H < 152$  GeV @95% CL

LEPEWWG/ZFitter



When  $m_H$  is known it will be time to review implications of influential BSM physics on all EW precision measurements

- 4th generation
- SUSY
- Higgs triplets
- etc. etc.

Moriond EW2012 EXP Summary -- Alain Blondel

## Latest updates (17/3/2012)...



Rencontres de Moriond  
QCD and High Energy Interactions

### A closer look: LHC

What has changed since December 13th?

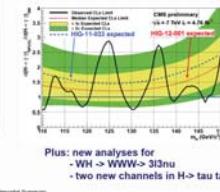
ATLAS

Searches performed in 12 distinct channels using the full 2011 dataset

Higgs Decay channel	$m_H$ Range	$L [fb^{-1}]$
low- $m_H$ , good mass resolution		
$H \rightarrow WW \rightarrow ll\nu\nu$	110-150	4.8
$H \rightarrow ZZ \rightarrow llpp$	110-150	4.8
low- $m_H$ , limited mass resolution		
$H \rightarrow WW \rightarrow ll\nu\nu$	110-300-600	4.7
$H \rightarrow ZZ \rightarrow ll\nu\nu$	110-150	4.7
$H \rightarrow \tau^+\tau^- \rightarrow l\nu\tau\tau\nu$	110-150	4.7
$H \rightarrow \tau^+\tau^- \rightarrow \tau\tau\nu\tau\nu$	110-150	4.7
high- $m_H$		
$H \rightarrow ZZ \rightarrow ll\nu\nu$	200-300-600	4.7
$H \rightarrow ZZ \rightarrow llpp$	200-300-600	4.7
$H \rightarrow WW \rightarrow llpp$	300-600	4.7

update on full statistics for all channels!

ATLAS and CMS have very similar sensitivity in basically all channels at the moment



Plus: new analyses for  
 $-WH \rightarrow WWW \rightarrow ll\nu\nu$   
two new channels in  $H \rightarrow \tau\tau\nu\tau\nu$

### How shall we study X(125)?

#### At LHC

It is there, and will do it.

The question: with which precision?  $O(10\%)$  or worse (assume  $600 fb^{-1}$ )

Effect of pile-up? Etc. etc.

do we need another machine to study more properties or more precisely?

Performance on couplings self couplings and invisible width?

#### At a linear collider ?

For 125 GeV Higgs, peak cross-section at  $\sim 250$  GeV =  $m_H + m_Z + 30$  GeV

But.. 250 GV of acceleration and luminosity at that energy still requires a large amount of power and superb alignment. Cost?

At a small  $e^+ e^-$  machine? LEP3 in LHC tunnel (see next slides)  
Much easier and cheaper than LC but not expandable.

#### At a muon collider ?

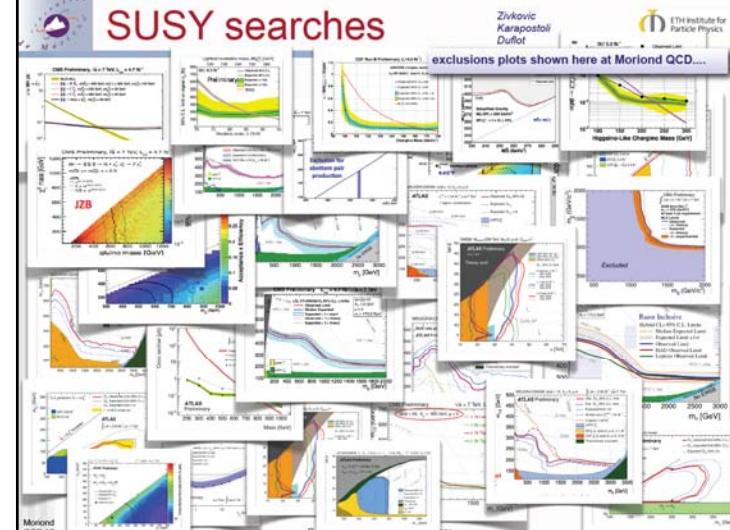
Feasibility study ongoing. Not an easy machine!

Ionization cooling (MICE experiment)

Virtue: s-channel production  $\mu^+ \mu^- \rightarrow H$ , exquisite energy calibration and very small energy spread if needed.

Moriond EW2012 EXP Summary -- Alain Blondel

## SUSY searches



## Revision lectures:

- Revisions lecture: 24/4 Poynting SLT
- Please fill in your preferences on poll

**Y3 PP revision topics**

Edit my poll | A. J. | 2 hours ago

Where: Revision week,

Please read before choosing

Choose either:  
(a) maximum 3 topics from the list, or  
(b) a single poll paper (as going through one paper would take most of a lecture)

Please read before choosing

Table view [Administration](#)

Most popular option: Summer 2008 exam | Close poll \*

General introduction to Particle Physics	Hadronic interactions and four momenta	Particle decay and resonance theory, experiments	Feynman diagrams, bubble chamber, with classification	Anisotropy, bubble chamber, with classification	Stable and unstable particles	Mass, identification and colour charge	Gauge charge	QCD	Fragilements, fissioning	Particle mass, strong and weak interaction, conservation laws	Gauge bosons, QCD and electroweak theory	CMB, Higgs boson, neutrinos and dark matter	Quantum entanglement and thermodynamics
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3 participants