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
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments' Results
- ☹ Future – introduction to accelerator physics ☹

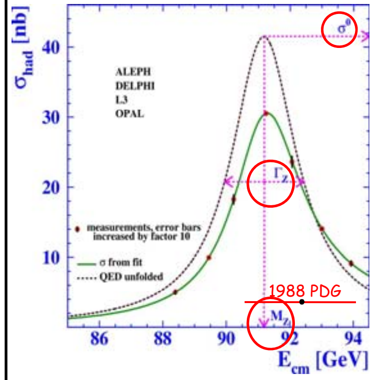
Today

- Lecture 21 (4 slides/page) - Z couplings, decay widths, couplings, Higgs
  - Martin and Shaw, pp. 225-229

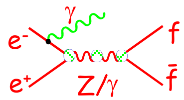
Previous lecture

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

LEP Lineshape: 1989+…final results



- 3 parameters: m_Z, Γ_Z, σ°_{had}
- Observe



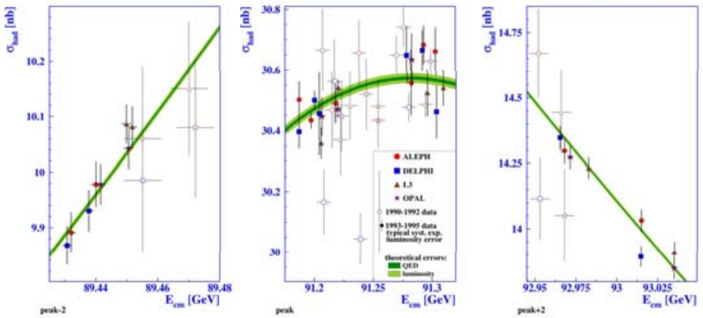
- …EW radiative corrections absorbed in effective couplings
- Deconvolve to Born cross-section
- Obtain

m_Z = 91,187.5 ± 2.1 MeV
Γ_Z = 2,495.2 ± 2.3 MeV
σ°_{had} = 41.540 ± 0.037 nb

Combined measurements, LepI sample

Final LEPI "Z⁰ lineshape" measurements
See Physics Reports,Vol. 427, Nos. 5-6, May 2006

Details of LepI Cross-Section Data



All 4 LEP experiments and years of LepI

No. of Neutrino Generations

- "Invisible width", $\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3\,\Gamma_\ell$
- No. of generations = $\Gamma_{inv} / \Gamma_\nu^{SM}$ **SM:** $\Gamma_\nu^{SM} = \frac{G_F m_Z^3}{6\pi\sqrt{2}}(c_v^2 + c_a^2)$ **≈166 MeV**
  - **Measure Γ_{inv}**
- c_v + c_a are vector and axial vector couplings of neutrino to Z
- **Direct**: measure $\sigma(e^+e^- \to \nu\bar{\nu}\gamma)$ soft γ + nothing else…challenging!
- **Indirect**: measure m_Z, Γ_Z, R_ℓ, σ°_{had}

$$\sigma^\circ_{had} \equiv \frac{12\pi\Gamma_e\Gamma_{had}}{(m_Z\Gamma_Z)^2}$$

$$\Gamma_{inv} / \Gamma_\nu^{SM} = \left(\frac{12\pi}{m_Z^2\,\sigma^\circ_{had}}\right)^{\frac{1}{2}} - R_\ell - 3$$

⇒ $N_\nu = 2.9841 \pm 0.0083$ **for $m_\nu \le \frac{1}{2} m_Z$ ~ 45 GeV**

- For N_ν = 3, width from new Z decay modes = -2.7 ± 1.6 MeV
- Still room for heavy or sterile neutrinos

P and T transformations

Observable	Parity transform
Position, **r**	-**r** (vector)
Momentum, **p**	-p (vector)
Spin, σ	σ (axial vector)
Longitudinal polarisation, σ.**p**	-σ.p (pseudoscalar)
Electric field, **E**	-**E** (vector)
Magnetic field, **B**	**B** (axial vector)
Magnetic dipole moment, σ.**B**	σ.**B** (scalar)
Electric dipole moment, σ.**E**	-σ.**E** (pseudoscalar)

Z couplings to fermions

fermion	c_v	c_a
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2} + 2\sin^2\theta_W$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2} - (4/3)\sin^2\theta_W$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2} + (2/3)\sin^2\theta_W$	$-\frac{1}{2}$

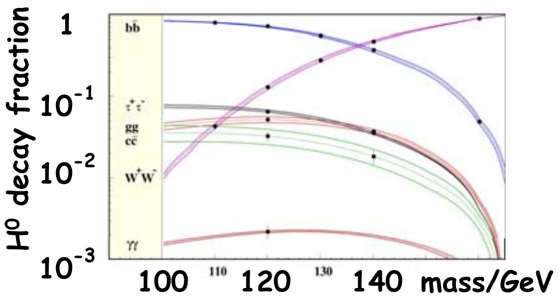
$c_v/c_a = 1-4Q_f \sin^2\theta_W$

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

θ_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, $t\bar{t}$ 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, $|(o_i - \text{SM fit}_i)| / \text{error}(o_i)$

See LEP Electroweak Working Group

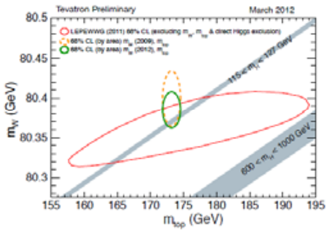
http://lepewwg.web.cern.ch/LEPEWWG/

Now m_W is the most contraining variable in the indirect limit to m_H

With M_W = 80385±15 MeV

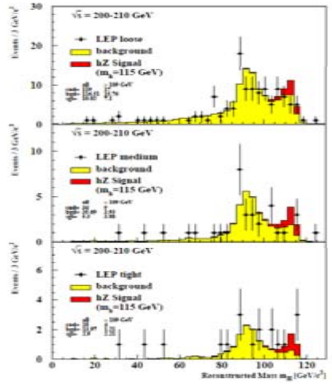
$M_H = 94^{+29}_{-24}$ GeV
M_H < 152 GeV @95% CL

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.

LEP2 SM Higgs Search (c. 2001)

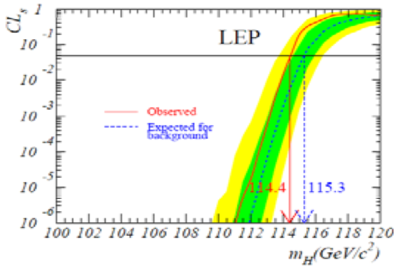


- Plots for illustrative purpose only
- Actual limits dervied from comlpicated statistical analysis
- Direct search in e^+e^- collider, very sound limit

Individual LEP experiments

LEP excludes a 114.4 GeV Higgs boson @ 95% CL. (expected 115.3 GeV)

	Exp.	Obs.
ALEPH	113.5	111.4
DELPHI	113.3	114.1
L3	112.4	112.0
OPAL	112.7	112.7



Pierre Lutz /SACLAY

Individual pp,vN, e^+e^-experiments combined

Updated "all data" results, summer 2010

Direct SM higgs search at LEP (e^+e^-)

LEP excludes a 114.4 GeV Higgs boson @ 95% CL. (expected 115.3 GeV)

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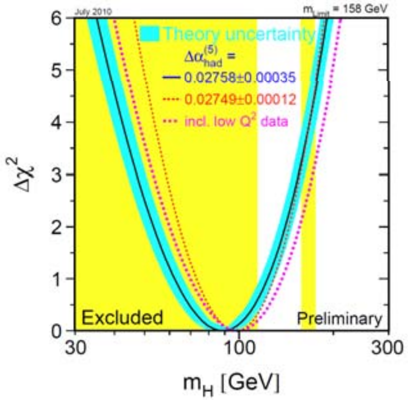


http://lepewwg.web.cern.ch/LEPEWWG/

Higgs search mod-Nov. 2011

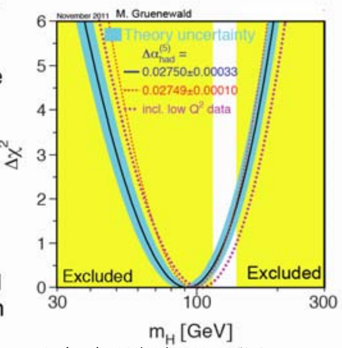
Conclusions

Little room left for the SM Higgs !
$114<m_H<141$ GeV @ 95% CL

LHC experiments will analyze the x3 data already collected before 2012 Winter Conferences

Tevatron will provide the final results on 10 fb^{-1} by the 2012 Summer Conferences

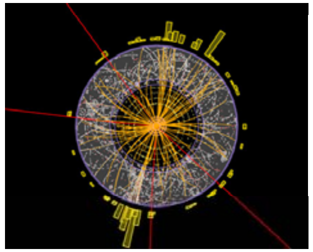
On the same time scale there will be a combination LHC + Tevatron

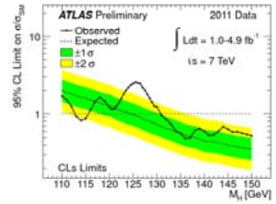


[Rolandi, 18/11/2011, HCP Paris]

Recently

Status reports from ATLAS and CMS, 13 Dec. 2011
ATLAS interesting event and summary





"We have restricted the most likely mass region for the Higgs boson to 115-130 GeV, and over the last few weeks we have started to see an intriguing excess of events in the mass range around 125 GeV," explained ATLAS experiment spokesperson Fabiola Gianotti. *"This excess may be due to a fluctuation, but it could also be something more interesting. We cannot conclude anything at this stage. We need more study and more data. Given the outstanding performance of the LHC this year, we will not need to wait long for enough data and can look forward to resolving this puzzle in 2012."*

Latest updates (17/3/2012)…

Rencontres de Moriond
QCD and High Energy Interactions

A closer look: LHC

R. Bernhard
A. Bornheim

- What has changed since December 13th?

ATLAS

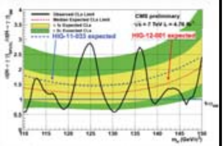
Searches performed in 12 distinct channels using the full 2011 dataset

Higgs Decay channel	m_H Range	L [fb^{-1}]
low-m_H, good mass resolution		
$H\to\gamma\gamma$	110-150	4.9
$H\to ZZ\to \ell\ell\ell\ell$	110-600	4.8
low-m_H, limited mass resolution		
$H\to WW\to \ell\nu\ell\nu$	110-200-300-600	4.7
$VH\to b\bar{b}$	110-130	4.6
$H\to\tau^+\tau^-\to\ell\ell 4\nu$	110-150	4.7
$H\to\tau^+\tau^-\to\ell\tau_{had}3\nu$	110-150	4.7
$H\to\tau^+\tau^-\to\tau_{had}\tau_{had}2\nu$	110-150	4.7
high-m_H		
$H\to ZZ\to\ell\ell\nu\nu$	200-280-600	4.7
$H\to ZZ\to\ell\ell qq$	200-300-600	4.7
$H\to WW\to\ell\nu qq'$	300-600	4.7

update on full statistics for all channels!

CMS

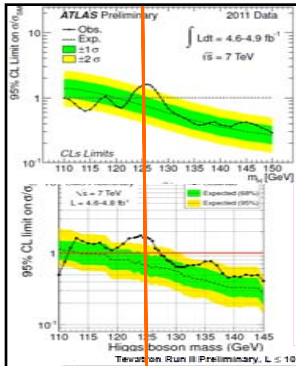
- Main update to final Higgs combination : $H\to\gamma\gamma$ MVA analysis, inputs very similar to published cut and count analysis.
- Goal : Optimize use of high quality events in terms of detector performance and kinematics.
- MVA based Photon ID and MVA based diphoton event classification.
- Four non-VBF event classes split based on diphoton classifier output, replacing categorization in |η| and R9 (measure of photon interaction with tracker material which degrades the performance).
- One VBF event class with dijet tagged events, just lower cut on diphoton event classification.



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

Plus: new analyses for
- WH -> WWW-> 3l3nu
- two new channels in H-> tau tau

Moriond QCD 12 — Dissertori : Experimental Summary — 52



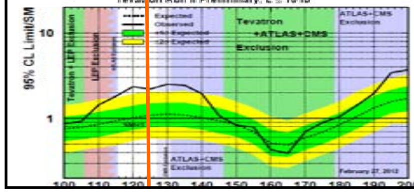
Both ATLAS and CMS exclude a SM scalar boson up to ~550 GeV
except in range (117-128 GeV): excess 2.5-2.9 σ at 125-126 GeV/c² (consistent)

ATLAS : γγ and ZZ
CMS : γγ
CDF+ D0 mostly b̄b&WW

Too soon to claim even evidence, but…
'Who would bet against Higgs boson @125 GeV?

My guess: Look Elsewhere + Look There
→ CL probably >~ local significance of 2d experiment

More data in 2012→ 5σ and more channels!



EXP Summary -- Alain Blondel

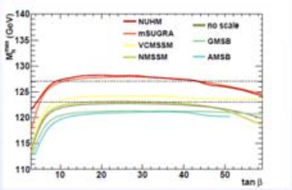
We should wait until the « 125 GeV effect » is either killed or established.
A particle decaying in two photons is not spin 1 and more probably spin 0

Is it elementary? Does it have all properties of the SM scalar of EBH et al?
It will be exciting to investigate this NEW object!

Just as for EWRCs, its discovery would eliminate a great number of hypotheses.

Consequences of a 125 GeV Higgs on constrained MSSM scenarios

Maximal Higgs masses



A. Arbey, M. Battaglia, A. Djouadi, F. M., J. Quevillon, Phys.Lett. B708 (2012) 162

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
M_h^{max}	121.0	121.5	128.0	123.0	123.5	124.5	128.5

End of AMSB and GMSB in their minimal versions!

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 600fb^{-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 ~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.

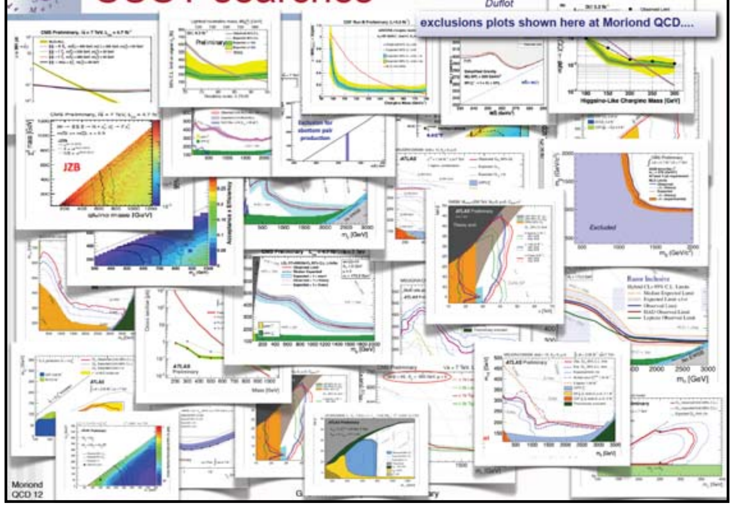
At a muon collider ?
Feasibility study ongoing. Not an easy machine!
Ionization cooling (MICE experiment)
Virtue: s-channel production $\mu^+ \mu^- \to H$, exquisite energy calibration and very small energy spread if needed.

SUSY searches

Zivkovic
Karapostoli
Duflot

ETH Institute for Particle Physics

exclusions plots shown here at Moriond QCD....



Summary 1

ETH Institute for Particle Physics

- Some numbers:
  - Nr. of talks I listened to: 93
  - Record speaker: 43 slides in 15+ mins
  - Record Nr. of spoken words/talk: ~3000
  - Record Nr. of analyses/talk: 21
  - Nr. of limit/exclusion plots shown: > 200 at 95% CL
  - Numbers most often mentioned: 3.2×10^{-9} and 125
- Some recommendations
  - if you like to do extensive skiing at Moriond: don't accept to give the summary talk
  - if you like some good glass of red wine at dinner: don't accept to give the summary talk
  - if you like to hang out at the Hotel bar in the evening: don't accept to give the summary talk
  - if you like to learn a lot in a short time: accept to give the summary talk

Revision lectures:

- Revsions lectures x2: 30/4, 3/5 usual place/times
- Please let me know your preferences
  - Will distribute URL by email