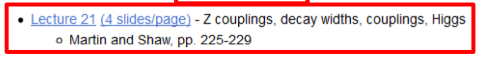
Outline

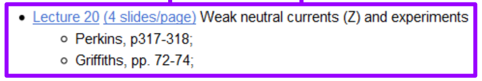
- Relativistic Kinematics
  - (4-momentum)2 invariance, invariant mass
  - Hypothesis testing, production thresholds
  - Cross-sections, flux and luminosity, accelerators
  - Particle lifetime, decay length, width
- Classification of particles
  - Fermions and bosons
  - Leptons, hadrons, quarks
  - 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;

For e^+e^- experiments

- **Vertex detector** – Usually Si-based, ~10um pixel or strip readout, measures displaced decay vertices (and improves momentum measurement)
- **Tracking chamber** – measures momentum from curvature in B field; ionisation of gas and (in drift chamber) readout on sense wires or (in TPC) end plates. The most recent designs for future accelerators consider using Si detectors.
- **Magnetic field (solenoid) - provides** bending of charged particle trajectories in plane perpendicular to beam axis. (May be located in front or after calorimeters.)
- **EM calorimeter** – sampling or homogeneous, measures: full energy of electrons, photons; fraction for charged hadrons; minimal amount for muons

For e^+e^- experiments

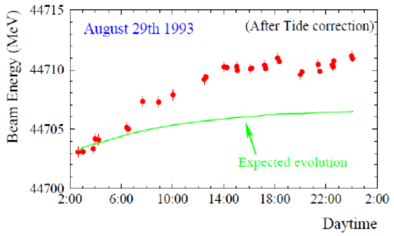
- **Hadronic calorimeter** – sampling, measures energy of hadrons (especially neutral hadrons).
- **Muon detectors** – outermost detector, any particle that passes through all previous material is assumed to be a muon (almost all others stopped in hcal or previous).
- **Luminosity detectors** – e.m. calorimeters located at very small angles to beam axis (~40 mrad), detect high energy e^+e^- from Bhabha scattering process, comparison with theoretical cross-section for which gives luminosity at the experiment
- At LEP, there were 4 detectors: Aleph, Opal ("General Purpose Detectors" using established technology); Delphi ("General purpose detector" with emphasis on new technology); L3 (emphasis on muonic final states, very small main tracking system)

Z boson mass determination

- Achieved relative precision of ~10^{-5} on Z boson mass, m_Z
- Not possible by "direct reconstruction" of kinematics of observed particles (experimental resolutions)
- Achieved by
  - Observing very large number of events (Z^0 resonance enhances cross-section by ~ 5000 for E_{cm}~m_Z)
  - Classifying final states
  - Using "N=Lσ"to determine cross-section
  - Comparing measured cross-section with *very accurate theoretical description* of $\sigma(e^+e^-\rightarrow ff)$ as $f(m_{Z,}, \Gamma_{z,} E_{cm,} \dots)$
    - ⇒ Requires many higher order diagrams to be calculated
- Experimental determination of centre-of-mass energy ("LEP beam energy", lecture 20) a particularly hard measurement, emphasis on systematic uncertainties…

LEP beam energy measurement I

- Precise beam energy by "resonant depolarisation" measurements
  - A single beam of polarised e^- is stored in the LEP accelerator and the measured precession frequency of e^- spins allows E_{beam} to be measured to a precision of <1 MeV (at E_{beam} ~45 GeV)
  - However, thiscannot be used during recording e^+e^- collisions, and therefore requires dedicated running of the accelerator.
  - This is only performed infrequently, because the time taken out for these measurements is time not available to collect Z decay events (reducing statistical precision of the cross-section measurements themselves).
  - Found to be ~ 10 MeV variation between these resonant depolarisation runs…



Systematics on LEP E_{beam} measurement I

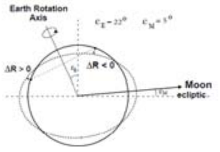
Earth tides

- Movement of moon/sun – Earth cause tides, which raise and lower the Earth crust (as well as the oceans)
- Variation at Geneva ~25cm vertical motion per day, inducing change in circumferences of LEP by ~ +/- 0.5mm.
- Although a small effect relative to the 27km circumference, this changes E_{beam} because the e^+e^- rotational frequency in the accelerator is fixed by the radio-frequency acceleration system and therefore induces a small offset from the centre of the quadrupole (focussing) magnets.
- This changes E_{beam} in the centre of each experiment
- The effect was predicted in advance, calculated, verified and taken into account by the experiments ☺

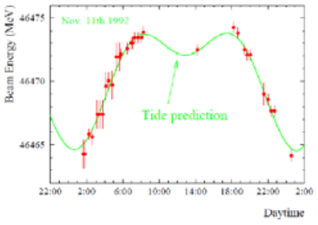
Tide bulge of a celestial body of mass M at a distance d :

$$\Delta R \sim \frac{M}{2d^3}(3\cos^2\theta - 1)$$

θ = angle(vertical,the celestial body)



Fall of 1992 : The historic tide experiment !



The total strain is 4 x 10^{-8} (ΔC = 1 mm)

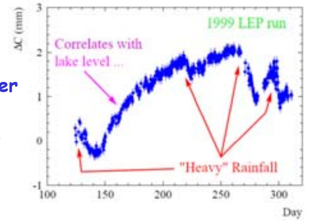
Systematics on LEP E_{beam} measurement II

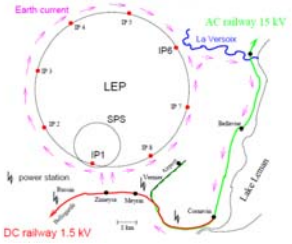
Water level

- Level of water in Lac Leman also affects the LEP circumference due to strain.
- The energy was observed to be correlated with the water level in the lake
- However, this is not as easy to calculate reliably (unlike earth tides) and so a small residual uncertainty was assigned due to this source.

Leakage from French trains (TGV)

- Relatively large uncertainties were still observed in E_{beam} over each day and not understood for years.
- The effect was finally correlated to the TGV timetable and stray leakage currents to pass along the (metal) LEP beam pipe.
- The effects were found to be absent during a measurement that took place by chance when there was an industrial strike which halted TGV operation.
  - The French electric trains are supplied by a DC current, some leaks to ground and completes a circuit by the path of least electrical resistance, causing different electrical currents in different sectors of the LEP accelerator, and these currents were found to be very highly correlated with the measured beam energy. This was the final source of uncertainty to be discovered!

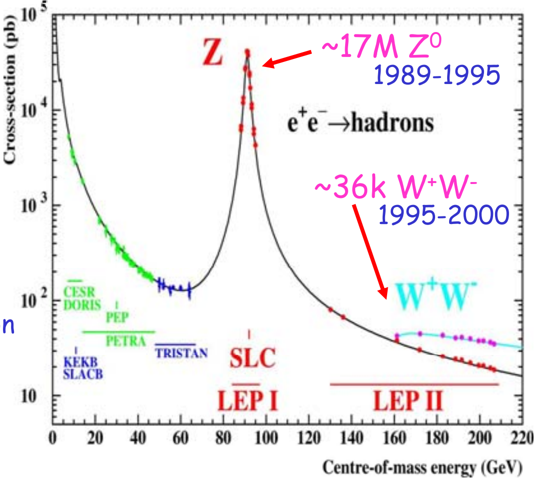




LEP: 1989-2001

- Precise measurements $\sqrt{s} \sim m_Z$
  - **No. neutrinos**
  - **Couplings, mixing angles**
- $f\bar{f}$ physics above m_Z
- W^+W^- production, properties
- Neutral boson pair production
- SM interpretations of data:
  - **Higgs mass**

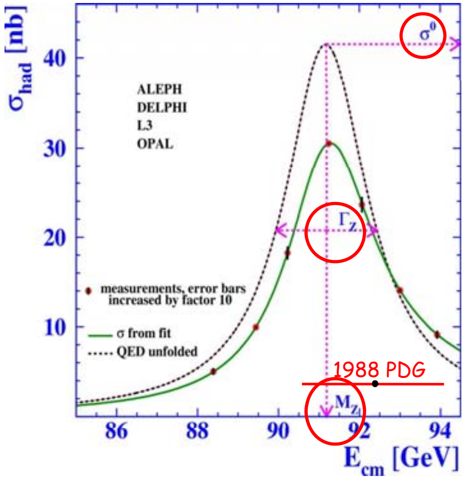
Data corrected for γ radiation



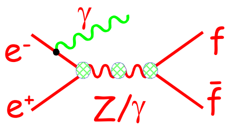
~17M Z^0
1989-1995

~36k W^+W^-
1995-2000

LEP Lineshape: 1989+…final results



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



- **…EW radiative corrections**

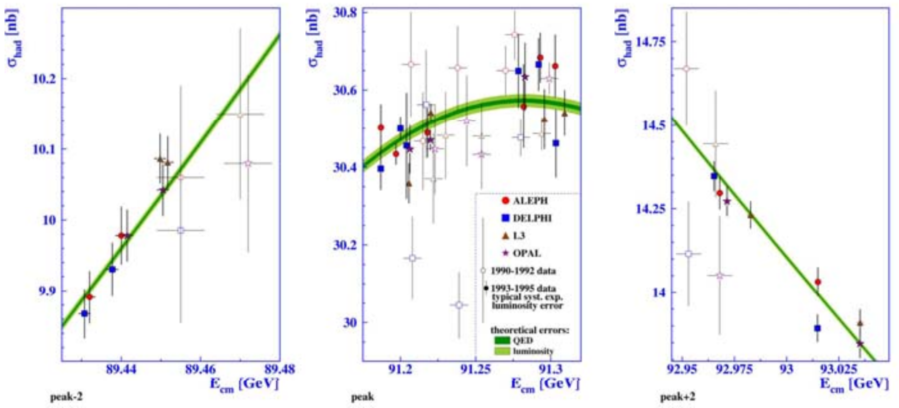
  absorbed in effective couplings
- Deconvolve to Born cross-section
- Obtain

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 "Z^0 lineshape" measurements
See Physics Reports,Vol. 427, Nos. 5-6, May 2006

Fine details of LepI Cross-Section Data



All 4 LEP experiments and years of "Lep I" (E_{cm}~m_Z)
Mass of Z^0 from cross-section measurement ("counting experiment")
Contrast with mass of W from measured energy and momenta ("direct reconstruction")

No. of Neutrino Generations

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

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

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

$$\Rightarrow \boxed{N_\nu = 2.9841 \pm 0.0083}$$ **for $m_\nu \leq \frac{1}{2} m_Z$ ~ 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", $M_w = M_Z \cos\theta_W$

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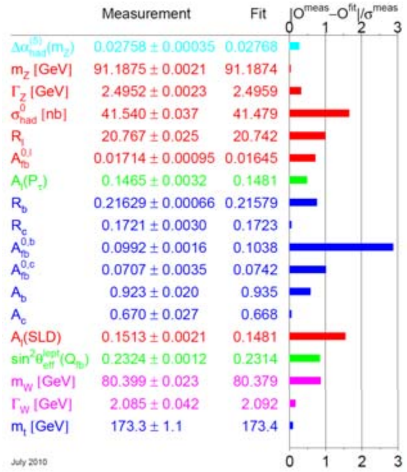
e.g. SM Combined Fits to Data



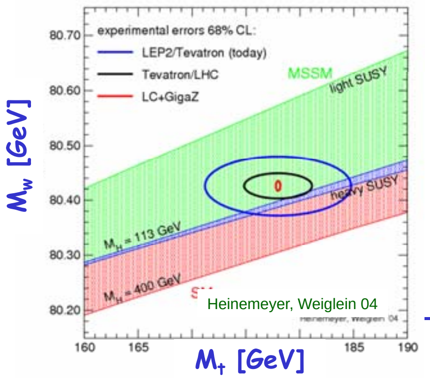
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	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
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

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

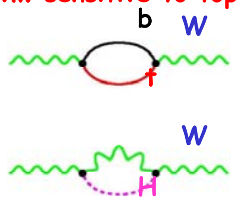
http://lepewwg.web.cern.ch/LEPEWWG/

Precise measurements consistency and predictions



Heinemeyer, Weiglein 04

Mw sensitive to top, Higgs via loops



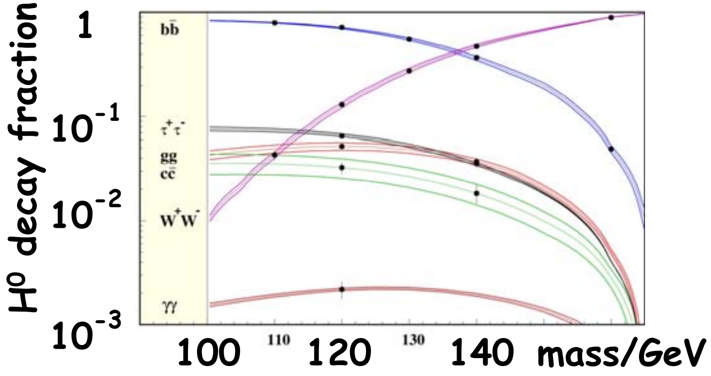
[Heinemeyer et al (LHCLC report)]

	δm_W (MeV)	δm_{top} (GeV)	$\delta\sin^2\theta_{eff} \times 10^5$
In 2004	34	3.9	17
TeV Run 2	16	1.4	29
LHC	15	1.0	14-20
ILC-GigaZ	7	0.1	1.3

[after Stirling, ECFA w/s, Durham Sep.04]

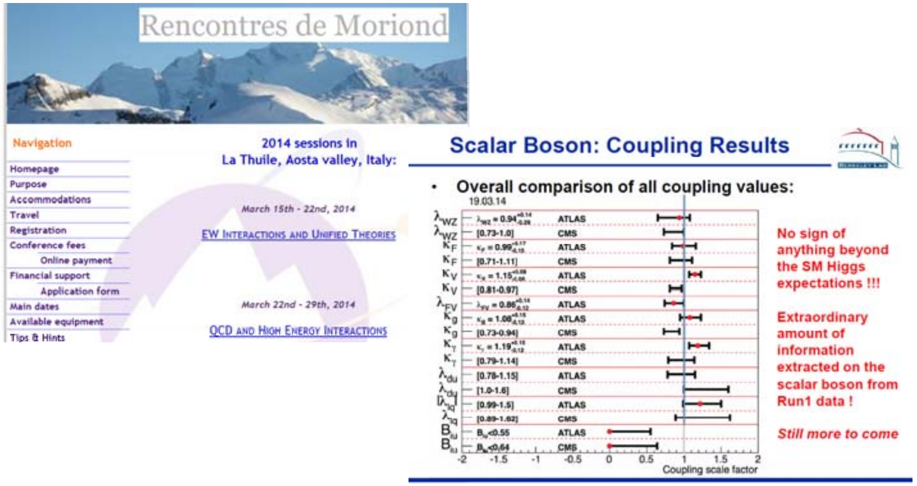
Higgs in e^+e^- collisions

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



No ambiguity in predictions
Very precise measurement only possible at lepton colliders

Latest updates (22/3/2014)



Rencontres de Moriond

Navigation

- Homepage
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- Available equipment
- Tips & Hints

2014 sessions in
La Thuile, Aosta valley, Italy:

March 15th - 22nd, 2014

EW INTERACTIONS AND UNIFIED THEORIES

March 22nd - 29th, 2014

QCD AND HIGH ENERGY INTERACTIONS

Scalar Boson: Coupling Results

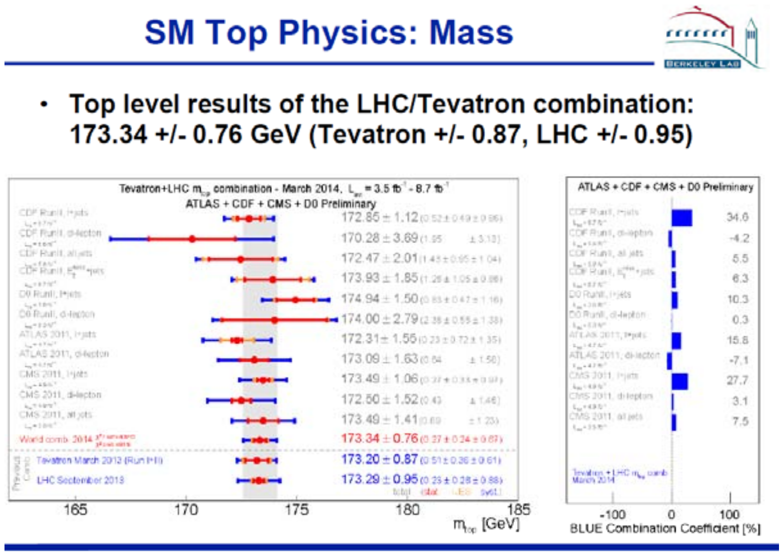
- Overall comparison of all coupling values:

No sign of anything beyond the SM Higgs expectations !!!

Extraordinary amount of information extracted on the scalar boson from Run1 data !

Still more to come

Top quark latest (22/03/2014)

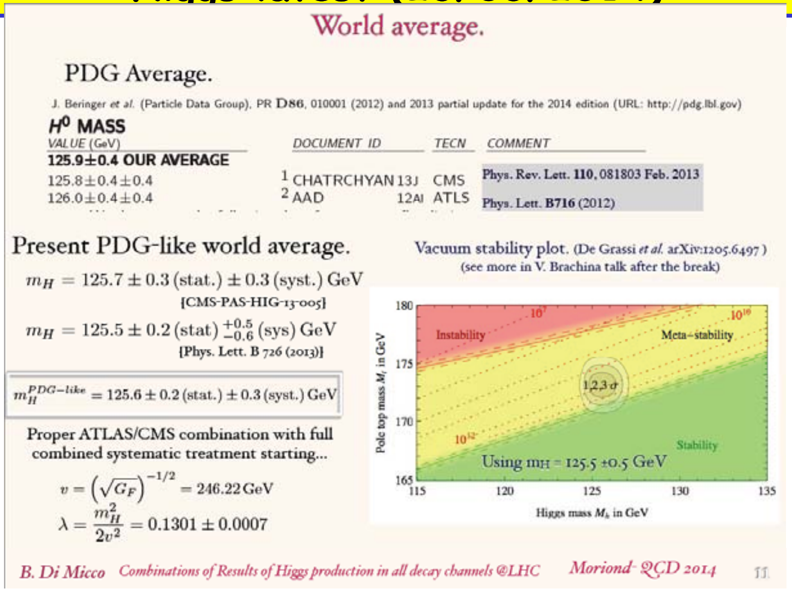


SM Top Physics: Mass

- Top level results of the LHC/Tevatron combination: 173.34 +/- 0.76 GeV (Tevatron +/- 0.87, LHC +/- 0.95)

[Kevin Einsweiler (Lawrence Berkeley Lab), Moriond EW summary, 22/03/2014
https://indico.in2p3.fr/getFile.py/access?contribId=227&sessionId=1&resId=0&materialId=slides&confId=9116]

Higgs latest (23/03/2014)



World average.

PDG Average.

J. Beringer *et al.* (Particle Data Group), PR D86, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

***H^0* MASS**

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125.9±0.4 OUR AVERAGE			
125.8±0.4±0.4	[1] CHATRCHYAN 13J	CMS	Phys. Rev. Lett. **110**, 081803 Feb. 2013
126.0±0.4±0.4	[2] AAD 12AI	ATLS	Phys. Lett. **B716** (2012)

Present PDG-like world average.

$$m_H = 125.7 \pm 0.3\,(\text{stat.}) \pm 0.3\,(\text{syst.})\ \text{GeV}$$

[CMS-PAS-HIG-13-005]

$$m_H = 125.5 \pm 0.2\,(\text{stat})\ ^{+0.5}_{-0.6}\,(\text{sys})\ \text{GeV}$$

[Phys. Lett. B 726 (2013)]

$$\boxed{m_H^{PDG-like} = 125.6 \pm 0.2\,(\text{stat.}) \pm 0.3\,(\text{syst.})\ \text{GeV}}$$

Proper ATLAS/CMS combination with full combined systematic treatment starting...

$$v = \left(\sqrt{G_F}\right)^{-1/2} = 246.22\,\text{GeV}$$

$$\lambda = \frac{m_H^2}{2v^2} = 0.1301 \pm 0.0007$$

Vacuum stability plot. (De Grassi *et al.* arXiv:1205.6497)
(see more in V. Brachina talk after the break)

B. Di Micco *Combinations of Results of Higgs production in all decay channels @LHC* *Moriond- QCD 2014* 11

[Biagio di Micco (Roma), Moriond QCD, Higgs session, 23/03/2014
http://moriond.in2p3.fr/QCD/2014/SundayMorning/DiMicco.pdf]

Revision lectures:

- Revsion lecture: Thurs. 1 May, West 117
- Please fill in your preferences on doodle poll
- To be linked from course web page (last year's shown below, to update this week)

Y3 PP revision topics

Where: Revision week.

************************ Please read before choosing **

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

************************ Please read before choosing **********************************

Most popular option: Summer 2008 exam | Close poll

	General introduction to Particle Physics	Relativistic kinematics and four momenta	Particle decays and hypothesis testing	Fixed target and colliding beam experiments	synchrotron radiation, particle lifetime, width and classifications	static quark model	meson and baryon multiplets	baryon wavefunction and colour charge	colour charge	QCD	Fragmentation, running couplings	Particle decays, strong and weak decays, conservation rules	Quark flavour conservation, CKM matrix	CKM matrix, heavy flavour production and decay	Identifying interactions and charmonium
3 participants															