

Previous lecture

- Quark content of mesons/baryons
 - ▶ flavour quantum number, e.g. $B^0=bd$
- Feynman diagrams (process description only, no calc.)
 - ▶ scattering and annihilation
- Δ^{++} decay (strong + weak, no e.m.)
 - ▶ $\Delta^{++} \rightarrow p\pi^+$ (strong, $\tau \sim 10^{-23}s$)
 - ↳ $\pi^+ \rightarrow \mu^+\nu_\mu$ (weak, $\tau \sim 10^{-8}s$)
- Course material will be updated lecture by lecture on <https://www.ep.ph.bham.ac.uk/twiki/bin/view/General/Y2Neutrinos>

Lecture Content

- Approx. lecture content
 1. PP intro
 2. PP intro.
 3. v props 1: strong/e.m./weak, lepton number, number of neutrino generations
 4. v props 2: v existence
 - Examples of decay/production
 5. Neutrino mass
 - Fermi-Kurie plot
 - Phase space kinematics/4-momentum
 6. Parity and CP violation... (why so important in lepton sector?)
 - Wu et al., ^{60}Co experiment
 7. Detection & observation
 - Liquid, solid, bubble chamber
 - "Direct" methods (DONUT)
 8. Solar and atmospheric neutrinos
 - Puzzle: relative abundances != SSM prediction
 - Two-flavour neutrino oscillation formalism
 9. Neutrino oscillations and mixing
 - Possible solutions to solar/atm. v problems
 10. Current and future experiments
 - SK, SNO, KAMLAND, CHOOZ
 - MINOS, miniBOONE...
 - NDBD (NEMO, etc.)
 - JPARC, vF,
 11. Implications for cosmology
 - Open vs. closed scenarios. various m, regions
 - v as DM candidate?
 - Subject outlook (JPARC, MICE, Neutrino Factory, ...)

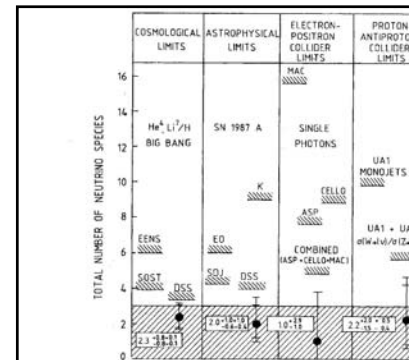
Today

- Finish strong/weak/e.m. comparison
- Baryon number
- Neutrino properties
 - ▶ Lepton number
 - ▶ Number of ν flavours
 - ▶ [Existence]

See also

Winter: Sect. 2.1, 2.3

Sutton ("spaceship neutrino"), chapter 2



From Denegri, Sadoulet and Spiro, Rev. Mod. Phys. 62, 1-42 (1990)

FIG. 34. Compilation of central values and 90% C.L. upper limits on the number of neutrino flavors N_ν from cosmology, astrophysics, and particle physics. The central value of N_ν from UA1 and UA2 is for the central theoretical expectation $R_\nu = 3.25$ and for $m_{top} = 50$ GeV. The upper limit is for the "worst case": $R_\nu = 3.15$ and $m_{top} = 50$ GeV. The abbreviations used for the cosmological and astrophysical limits are EENS = Ellis *et al.*, 1986; SOST = Steigman *et al.*, 1986; K = Krauss, 1987; EO = Ellis and Olive, 1987; SDJ = Shaeffer *et al.*, 1987; and DSS = this paper.

LEP1 Final States

1st LEP event
13-aug-1989

LEP expt., e.g. OPAL

Electromagnetic calorimeter
"endcap"
1132 lead glass blocks
Front face $\sim 10 \times 10 \text{ cm}^2$
Weight $\sim 25 \text{ kg/block}$

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

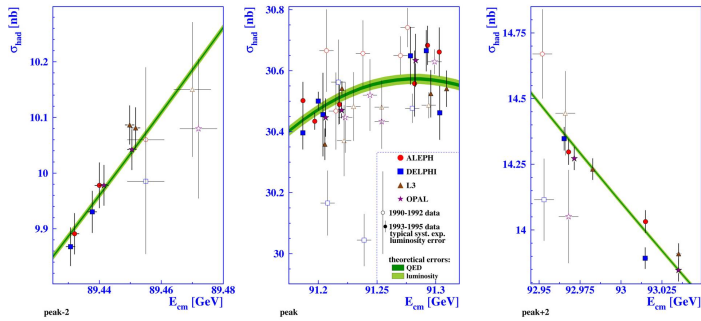
LEP Lineshape: 1989+...

- 3 parameters: $m_Z, \Gamma_Z, \sigma_{had}^0$
- Observe $e^+e^- \rightarrow Z/\gamma \rightarrow f\bar{f}$
- ...EW radiative corrections absorbed in effective couplings
- Deconvolve to Born cross-section
- Obtain

$m_Z = 91,187.5 \pm 2.1 \text{ MeV}$
 $\Gamma_Z = 2,495.2 \pm 2.3 \text{ MeV}$
 $\sigma_{had}^0 = 41.540 \pm 0.037 \text{ nb}$

Combined measurements, LepI sample

Details of LepI Cross-Section Data



All 4 LEP experiments and years of LepI

No. of Neutrino Generations

■ "Invisible width", $\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3\Gamma_l$
 ■ No. of generations = $\Gamma_{inv} / \Gamma_{\nu}^{SM}$ SM: $\Gamma_{\nu}^{SM} = \frac{G_F m_Z^3}{6\pi\sqrt{2}} (g_{\nu,\nu}^2 + g_{\nu,\nu}^2) \approx 166 \text{ MeV}$
 ▶ Measure Γ_{inv}

■ Direct: measure $\sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma)$ soft γ + nothing else...challenging!

■ Indirect: measure $m_Z, \Gamma_Z, R_l, \sigma_{had}^o$ $\sigma_{had}^o \equiv \frac{12\pi\Gamma_e\Gamma_{had}}{(m_Z\Gamma_Z)^2}$

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

$$\Rightarrow N_{\nu} = 2.9841 \pm 0.0083 \quad \text{for } m_{\nu} \leq \frac{1}{2}m_Z \sim 45 \text{ GeV}$$

■ For $N_{\nu} = 3$, width from new Z decay modes = $-2.7 \pm 1.6 \text{ MeV}$

■ Still room for heavy or sterile neutrinos

Beta decay spectrum

1 History

Pauli, 1927

[from Winter, Neutrino Physics, p2]

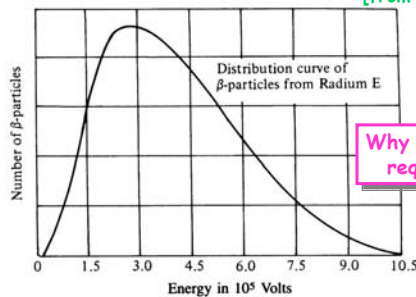


Fig. 1 Continuous beta spectrum of RaE.

■ Surprise: continuous not discrete energy distribution

■ Why?