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 decay, with weak decay of π^+)
  - $\Delta^{++} \rightarrow p\pi^+$ (strong, $\tau \sim 10^{-23}$s)
    - └─► $\pi^+ \rightarrow \mu^+\nu_\mu$ (weak, $\tau \sim 10^{-8}$s)

Today

- Baryon number
- Neutrino properties
  - Lepton number
  - Number of ν flavours

<u>See also</u>
Winter: Sect. 2.1, 2.3
Sutton ("spaceship neutrino"), chapter 2

Lecture Content

- Approx. lecture content
  1. PP intro
  2. PP intro.
     - Feynman diagrams; strong/e.m./weak
  3. ν props 1:, baryon and lepton numbers; no. neutrino generations,
  4. ν props 2: lepton no., ν 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. ν problems
  10. Current and future experiments
      - SK, SNO, KAMLAND, CHOOZ
      - MINOS, miniBOONE,..
      - NDBD (NEMO, etc.)
      - JPARC, νF,
  11. Implications for cosmology
      - Open vs. closed scenarios. various m_ν regions
      - ν as DM candidate?
      - Subject outlook (JPARC, MICE, Neutrino Factory, …)

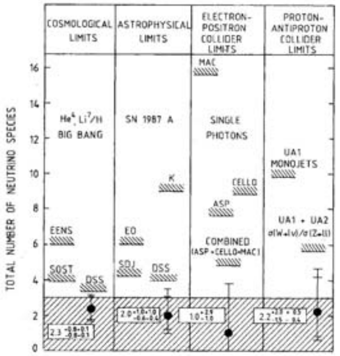
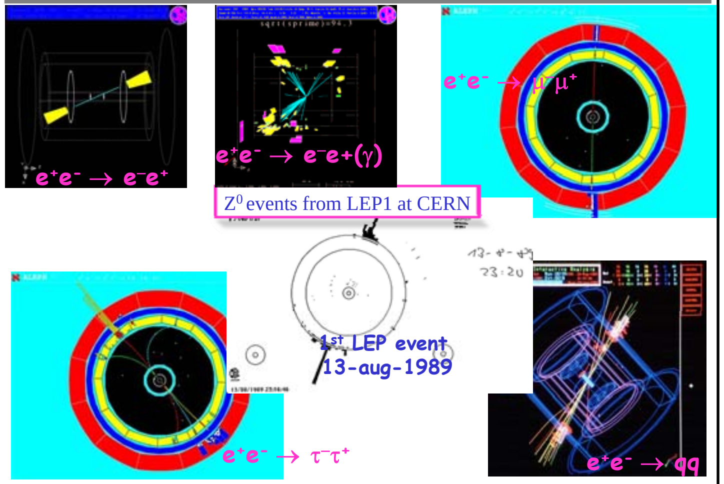


FIG. 34. Compilation of central values and 90% C.L. upper limits on the number of neutrino flavors N_ν from cosmology, astrophysics, and particle physics. The central value of N_ν from UA1 and UA2 is for the central theoretical expectation R_σ=3.25 and for m_{top}=50 GeV. The upper limit is for the "worst case:" R_σ=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.

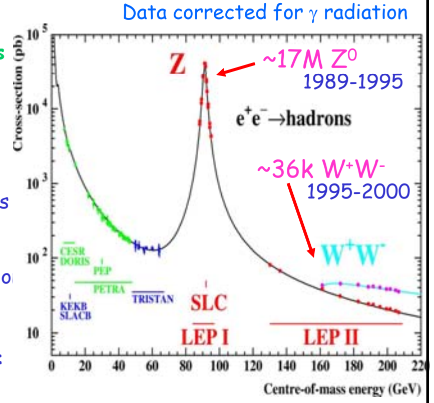
From Denegri, Sadoulet and Spiro, Rev. Mod. Phys. 62, 1-42 (1990)

Q: How do these reactions help to measure no. ν generations?

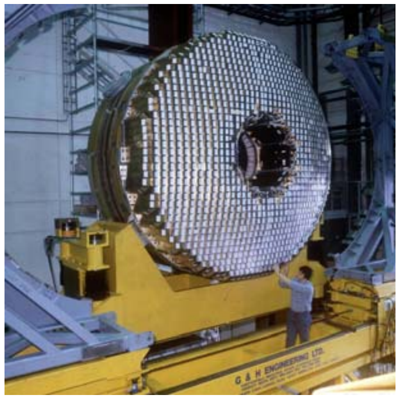


LEP: 1989-2001

- 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 productio
- SM interpretations of data:
  - **Higgs mass**

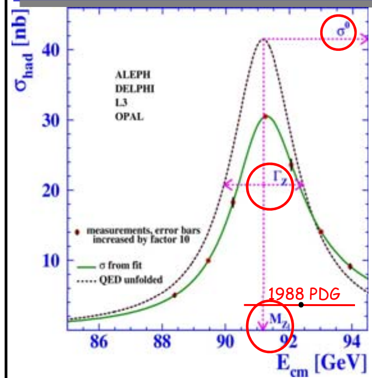


LEP expt., e.g. OPAL



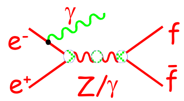
Electromagnetic calorimeter "endcap"
1132 lead glass blocks
Front face ~10x10cm²
Weight ~25kg/block

LEP Lineshape: 1989+…



Combined measurements, LepI sample

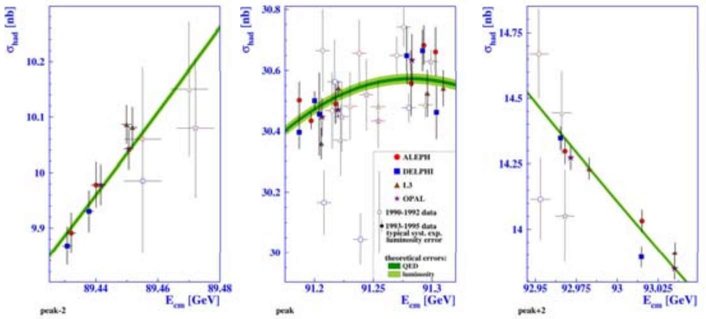
- 3 parameters: m_Z, Γ_Z, σ°_{had}
- Observe



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

$m_Z = 91{,}187.5 \pm 2.1$ MeV
$\Gamma_Z = 2{,}495.2 \pm 2.3$ MeV
$\sigma^{\circ}_{had} = 41.540 \pm 0.037$ nb

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:** $\Gamma_\nu^{SM} = \frac{G_F m_Z^3}{6\pi\sqrt{2}} (g_{v,\nu}^2 + g_{a,\nu}^2) \approx 166$ **MeV**
  - **Measure Γ_{inv}**
- **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} $\quad \sigma^\circ_{had} \equiv \frac{12\pi\Gamma_e\Gamma_{had}}{(m_Z\Gamma_Z)^2}$

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

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

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