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
  - Virtual particles and range of forces
  - Strong and weak decays, conservation rules
  - Parity, charge conjugation, CP
  - Weak decays of quarks
  - Colour charge, QCD, gluons
  - Charmonium and upsilon systems
- Electroweak Interactions
  - Charged and neutral currents
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments
- Future - introduction to accelerator physics

Please see web page for specific references to textbooks and brief reviews from PDG. (Particularly if you are taking PP Group Studies.)

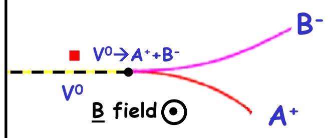
Reminder: **no lecture on Monday 30 Jan.** To be re-arranged later in term as required.

Further/Background Reading

Written lecture notes are not distributed but all transparencies/handouts are given below

- Lecture 1 (4 slides/page) - general introduction to Particle Physics
  - CERN Summer Student information - deadline 25 Jan. 2012
  - DESY Summer Student information - deadline 31 Jan. 2012
  - *Review of Quark Model*, in *2008 Particle Data Group Review of Particle Physics*, C. Amsler et al., published in Physics Letters B667, 1 (2008).
- Lecture 2 (4 slides/page) - Relativistic kinematics and four momenta
  - Griffiths, pages 89-103
  - Williams, page 159
  - Handout on kinematics and units
  - Units: see also Perkins (4th edition), pg 25.
- Lecture 3 (4 slides/page) - Particle decays and hypothesis testing
  - Bubble Chamber web (CERN/G.T.Jones)
  - Kinematics, from PDG, K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)
- Lecture 4 (4 slides/page) - Fixed target and colliding beam experiments
  - Perkins 4th edition, pp. 28-32 (acceleration in linear vs. circular machines)
  - Perkins 4th edition, pp 32-33 (collider vs. fixed target machines and luminosity)
  - Table of collider parameters - try to verify luminosity calculation for a few of these?
  - Brief review of accelerator physics of colliders from Particle Data Group, K. Nakamura et al., JPG 37, 075021 (2010) (http://pdg.lbl.gov)
  - See also: Tigner and Chao, Handbook of Accelerator Physics and Engineering (copy in Library)
  - USPAS - U.S. Particle Accelerator School
    - Course material - slides/lecture notes
    - Joint Accelerator Conference - proceedings for all major accelerator physics conferences

Hypothesis test example



- $V^0 \rightarrow A^+ + B^-$

Momenta in GeV/c

	p_x	p_y	p_z
A^+	1.628	0.0897	0
B^-	1.090	-0.0897	0

- Masses m_A, m_B unknown
- 3-momenta inferred from curvature
- Q: How to determine identity of V^0?
- We know that
  - $E_A=(p_A^2+m_A^2)^{1/2}$ $E_B=(p_B^2+m_B^2)^{1/2}$
  - $\underline{p}_V = \underline{p}_A + \underline{p}_B$ $\underline{E}_V = \underline{E}_A + \underline{E}_B$
  - $m_V = (E_V^2 - \underline{p}_V^2)^{1/2}$
- Assume A and B are lightest charged hadrons, π^+, m_π=139.6 MeV/c^2
- This gives $E_A=(1.628^2+0.0897^2+0.1396^2)^{1/2}$ = 1.636 GeV
- E_B=1.103 GeV

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- This gives $E_A=(1.628^2+0.0897^2 0.1396^2)^{1/2}$=1.636 GeV
- E_B=1.103 GeV
- Using these E_A and E_B, we obtain E_V and $\underline{p}_V$
  - $\underline{p}_V = \underline{p}_A + \underline{p}_B$ $\underline{E}_V = \underline{E}_A + \underline{E}_B$
- And from these, it follows that
  - $m_V = (E_V^2 - \underline{p}_V^2)^{1/2}$
  - $= ((1.103+1.628)^2 - (1.628+1.090)^2) = 0.338$ GeV/c^2 - unknown!
- Repeat above for A and B = K^+/K^-, m_K=494 MeV/c^2
  - Obtain m_V=1.020 GeV/c^2 i.e. ϕ(1020) - good hypothesis.

LEP Collider close to max. energy

Beam "lifetime" in e^+e^-

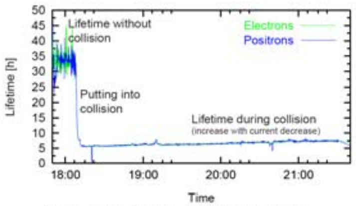


Figure 1: Evolution of beam lifetime in LEP.

R. Assmann et al, "Luminosity and Beam Measureents Used for Performance Optimisation in the LEP Collider", *EPAC*, Vienna, p. 265 (2000).

Luminosity vs. time (energy)

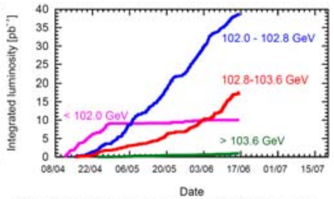


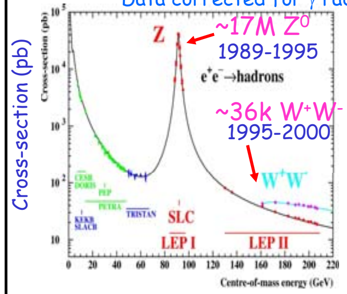
Figure 2: Luminosity production in 2000. The three anges correspond to 2, 1 and 0 klystrons overhead (right hand numbers, from top to bottom).

G. Arduini et al, "LEP Operation and Performance with 100 GeV Colliding Beams," EPAC, Vienna, p. 265 (2000).

Example: data rates

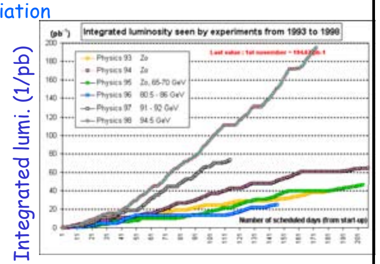
Physics cross-sections

Data corrected for γ radiation



Centre-of-mass energy (GeV)

Integrated collider lumi.



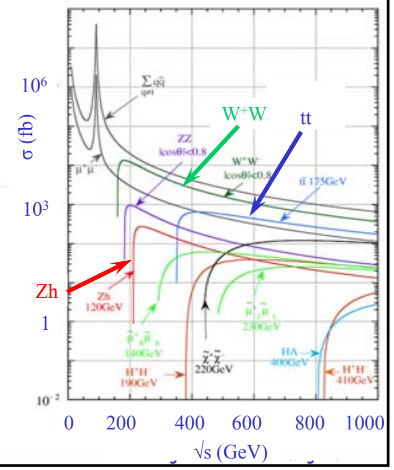
Days since start up

Example of machine parameters

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	ILC (TBD)
Physics start date	1979	2002	1989	TBD
Physics end date	2002	2008	2000	—
Maximum beam energy (GeV)	6	6	100 - 104.6	250 (upgradeable to 500)
Luminosity (10^{30} cm^{-2}s^{-1})	1280 at 5.3 GeV/beam	76 at 2.08 GeV/beam	24 at Z^0 100 at > 90 GeV	2×10^4
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	0.3†
Full crossing angle (μ rad)	±2000	±3300	0	14000
Energy spread (units 10^{-3})	0.6 at 5.3 GeV/beam	0.82 at 2.08 GeV/beam	0.7→1.5	1
Bunch length (cm)	1.8	1.2	1.0	0.03
Beam radius (μm)	H: 460 V: 4	H: 340 V: 6.5	H: 200 → 300 V: 2.5 → 8	H: 0.639 V: 0.0057
Free space at interaction point (m)	±2.2 (±0.6 to REC quads)	±2.2 (±0.3 to PM quads)	±3.5	±3.5
Luminosity lifetime (hr)	2-3	2-3	20 at Z^0 10 at > 90 GeV	n/a
Turn-around time (min)	5 (topping up)	1.5 (topping up)	50	n/a
Injection energy (GeV)	1.8-6	1.5-6	22	n/a
Transverse emittance ($10^{-9}\pi$ rad-m)	H: 210 V: 1	H: 120 V: 3.5	H: 20-45 V: 0.25 → 1	H: 0.02 V: 8×10^{-5} (at 250 GeV)
β^*, amplitude function at interaction point (m)	H: 1.0 V: 0.018	H: 0.94 V: 0.012	H: 1.5 V: 0.05	H: 0.02 V: 0.0004
Beam-beam tune shift per crossing (units 10^{-4})	H: 250 V: 620	e^-: 420 (H), 280 (V) e^+: 410 (H), 270 (V)	830	n/a
RF frequency (MHz)	500	500	352.2	1300
Particles per bunch (units 10^{10})	1.15	4.7	45 in collision 60 in single beam	2
Bunches per ring per species	9 trains of 5 bunches	8 trains of 3 bunches	4 trains of 1 or 2	2625

Higher energy e^+e^- colliders

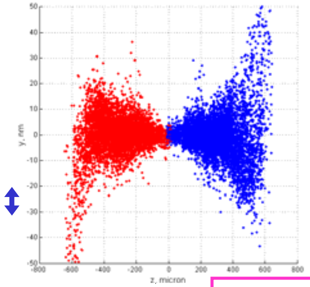
- In planning/R&D phase
- Physics motivations many
- Cross-sections small!
- Luminosity the issue!
- b/c-tagging with high purity/efficiency
  - e.g. Higgs branching ratios
- Precision Tracking
- Recoil mass measurements
- Jet energy resolution
- Multi jet final states, e.g.
  - ttbar
  - separation of WW/ZZ



Beam-Beam effects in future e⁺e⁻ machines

[c/o Andrei Seryi]

e^+ →



← e^-

10 nm (vertical)

1 mm (longitudinal)

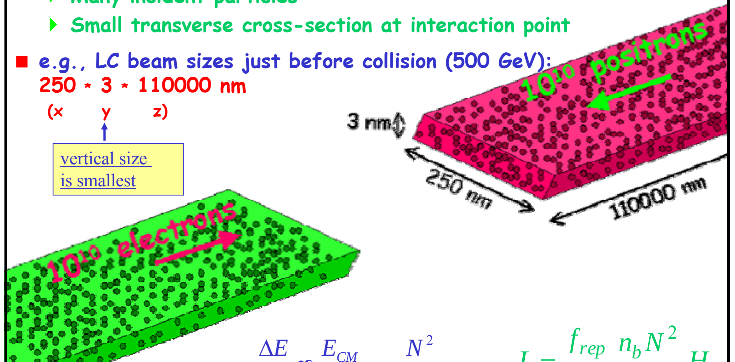
- Mutual focusing, "pinch" enhancement
- Large disruption – single pass machine
- Beam-beam effects, amplify initial vertical offsets
  - detect downstream, feedback, maintains lumi

Luminosity in future e⁺e⁻ machine

[c/o Andrei Seryi]

- High luminosity achieved by
  - Many incident particles
  - Small transverse cross-section at interaction point
- e.g., LC beam sizes just before collision (500 GeV):
  250 * 3 * 110000 nm
  (x y z)

vertical size is smallest



$$\frac{\Delta E}{E} \propto \frac{E_{CM}}{\sigma_z} \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D$$