PHYS 3446 – Lecture #14

Wednesday, Mar. 23, 2005

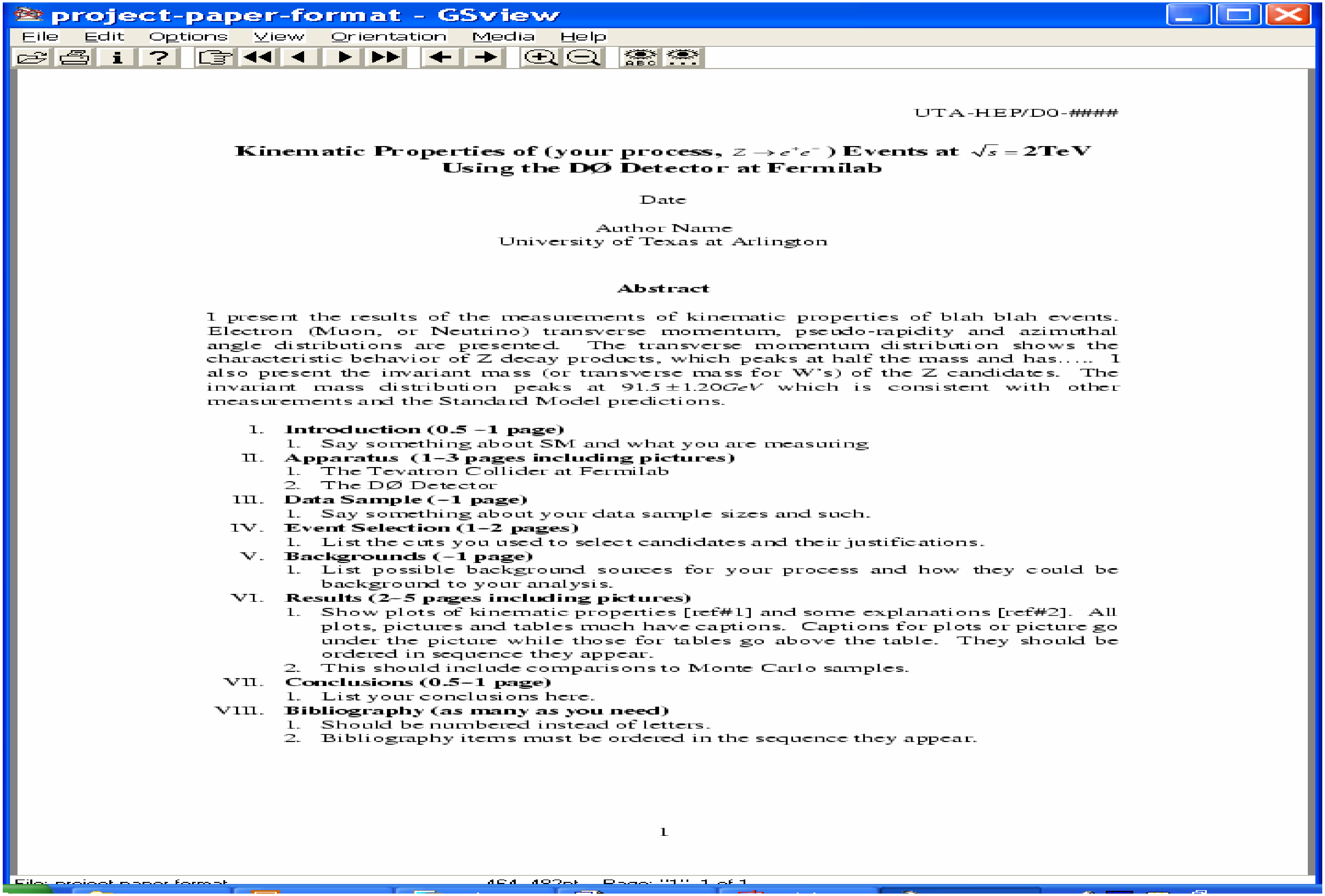
*Dr. **Jae** Yu*

- Elementary Particle Properties
  - Forces and their relative magnitudes
  - Elementary particles
  - Quantum Numbers
  - Gell-Mann-Nishijima Relations
  - Production and Decay of Resonances

Announcements

- Class Projects
  - Report papers are due on Friday, Apr. 22
    - The format of the paper will be posted on the class web page
  - Presentations will be on
    - Monday, Apr. 25: Z's (10+5 each)
    - Wednesday, Apr. 27: W's (10+5 each)
  - Papers constitute 20% while the presentations are 10%
- Project assignments
- Class assignments:
  - $W \rightarrow e\nu+X$: James, Carlos and Elisha
  - $W \rightarrow \mu\nu+X$: Jeremy and Jim
  - $Z \rightarrow ee+X$: Casey, David and Mathew
  - $Z \rightarrow \mu\mu+X$: John, Jacob and Sabine
- I am sure you guys have been analyzing but since there isn't too much time before the due, I'd suggest you to move rapidly on this.

Paper Template



UTA-HEP/DO-####

Kinematic Properties of (your process, $Z \rightarrow e^+e^-$) Events at $\sqrt{s} = 2$TeV
Using the DØ Detector at Fermilab

Date

Author Name
University of Texas at Arlington

Abstract

I present the results of the measurements of kinematic properties of blah blah events. Electron (Muon, or Neutrino) transverse momentum, pseudo-rapidity and azimuthal angle distributions are presented. The transverse momentum distribution shows the characteristic behavior of Z decay products, which peaks at half the mass and has….. I also present the invariant mass (or transverse mass for W's) of the Z candidates. The invariant mass distribution peaks at $91.5 \pm 1.20 GeV$ which is consistent with other measurements and the Standard Model predictions.

I. **Introduction (0.5 –1 page)**
   1. Say something about SM and what you are measuring
II. **Apparatus (1–3 pages including pictures)**
   1. The Tevatron Collider at Fermilab
   2. The DØ Detector
III. **Data Sample (–1 page)**
   1. Say something about your data sample sizes and such.
IV. **Event Selection (1–2 pages)**
   1. List the cuts you used to select candidates and their justifications.
V. **Backgrounds (–1 page)**
   1. List possible background sources for your process and how they could be background to your analysis.
VI. **Results (2–5 pages including pictures)**
   1. Show plots of kinematic properties [ref#1] and some explanations [ref#2]. All plots, pictures and tables much have captions. Captions for plots or picture go under the picture while those for tables go above the table. They should be ordered in sequence they appear.
   2. This should include comparisons to Monte Carlo samples.
VII. **Conclusions (0.5–1 page)**
   1. List your conclusions here.
VIII. **Bibliography (as many as you need)**
   1. Should be numbered instead of letters.
   2. Bibliography items must be ordered in the sequence they appear.

1

Forewords

- What are elementary particles?
  - Particles that make up matter in the universe
- What is the requirement for a particle to be an elementary one?
  - Cannot be broken into smaller pieces
  - Cannot have sizes
- The notion of "elementary particles" have changed from 1930's through present
  - In the past, people thought protons, neutrons, pions, kaons, ρ-mesons, etc, as elementary particles
- Why?
  - Due to the increasing energies of accelerators that allows us to probe smaller distance scales
- What is the energy needed to probe 0.1–fm?
  - From de Broglie Wavelength, we obtain

$$P = \frac{\hbar}{\lambda} = \frac{\hbar c}{\lambda c} = \frac{197\text{fm}-MeV}{0.1\text{fm}\,c} \approx 2000 MeV/c$$

Forces and Their Relative Strengths

- Classical forces:
  - Gravitational: every particle is subject to this force, including massless ones
    - How do you know?
  - Electromagnetic: only those with electrical charges
  - What are the ranges of these forces?
    - Infinite!!
  - What does this tell you?
    - Their force carriers are massless!!
  - What are the force carriers of these forces?
    - Gravity: graviton (not seen but just a concept)
    - Electromagnetism: Photons

Forces and Their Relative Strengths

- What other forces?
  - Strong force
    - Where did we learn this force?
      - From nuclear phenomena
      - The interactions are far stronger and extremely short ranged
  - Weak force
    - How did we learn about this force?
      - From nuclear beta decay
  - What are their ranges?
    - Very short
  - What does this tell you?
    - Their force carriers are massive!
    - Not really for strong forces
- All four forces can act at the same time!!!

Forces' Relative Strengths

- The strengths can be obtained through potential, considering two protons separated by a distance r.
- Magnitude of Coulomb and gravitational potential are

$$V_{EM}(r) = \frac{e^2}{r} \xrightarrow{\text{Fourier x-form}} V_{EM}(r) = \frac{e^2}{q^2}$$

$$V_g(r) = \frac{G_N m^2}{r} \xrightarrow{\text{Fourier x-form}} V_g(r) = \frac{G_N m^2}{q^2}$$

  - q: magnitude of the momentum transfer
- What do you observe?
  - The absolute values of the potential E decreases quadratically with increasing momentum transfer
  - The relative strength is, though independent of momentum transfer

$$\frac{V_{EM}}{V_g} = \frac{e^2}{G_N m^2} = \left(\frac{e^2}{\hbar c}\right)\frac{1}{\left(mc^2\right)^2}\frac{\hbar c^5}{G_N} = \left(\frac{1}{137}\right)\frac{1}{1GeV^2}\frac{10^{39}GeV^2}{6.7} \sim 10^{36}$$

Forces' Relative Strengths

- Using Yukawa potential form, the magnitudes of strong and weak potentail can be written as

$$V_S(r) = \frac{g_S^2}{r} e^{-\frac{m_\pi c^2 r}{\hbar c}} \xrightarrow{\text{Fourier x-form}} V_S(r) = \frac{g_S^2}{q^2 + m_\pi^2 c^2}$$

$$V_W(r) = \frac{g_W^2}{r} e^{-\frac{m_W c^2 r}{\hbar c}} \xrightarrow{\text{Fourier x-form}} V_W(r) = \frac{g_W^2}{q^2 + m_W^2 c^2}$$

  - g_W and g_s: coupling constants or effective charges
  - m_W and m_π: masses of force mediators
- The values of the coupling constants can be estimated from experiments

$$\frac{g_S^2}{\hbar c} \approx 15 \qquad \frac{g_W^2}{\hbar c} \approx 0.004$$

Forces' Relative Strengths

- We could think of π as the strong force mediator w/ $m_\pi \approx 140 MeV/c^2$
- From observations of beta decays, $m_W \approx 80 GeV/c^2$
- However there still is an explicit dependence on momentum transfer
  - Since we are considering two protons, we can replace the momentum transfer, q, with the mass of protons

$$q^2c^2 = m_p^2c^4 \approx 1GeV$$

Forces' Relative Strengths

- The relative strength between EM and strong potential is

$$\frac{V_S}{V_{EM}} = \frac{g_S^2}{\hbar c}\frac{\hbar c}{e^2}\frac{q^2}{q^2+m_\pi^2 c^2} = \frac{g_S^2}{\hbar c}\frac{\hbar c}{e^2}\frac{m_p^2 c^4}{m_p^2 c^4+m_\pi^2 c^2}$$

$$\approx 15\times 137\times 1 \approx 2\times 10^3$$

- And that between weak and EM is

$$\frac{V_{EM}}{V_W} = \frac{e^2}{\hbar c}\frac{\hbar c}{g_W^2}\frac{q^2+m_W^2 c^2}{q^2} = \frac{e^2}{\hbar c}\frac{\hbar c}{g_W^2}\frac{m_p^2 c^4+m_W^2 c^2}{m_p^2 c^4}$$

$$\approx \frac{1}{137}\times\frac{1}{0.004}\times 80^2 \approx 1.2\times 10^4$$

Interaction Time

- The ranges of forces also affect interaction time
  - Typical time for Strong interaction ~10^{-24}sec
    - What is this?
    - A time that takes light to traverse the size of a proton (~1 fm)
  - Typical time for EM force ~10^{-20} – 10^{-16} sec
  - Typical time for Weak force ~10^{-13} – 10^{-6} sec
- In GeV ranges, the four forces are different
- These are used to classify elementary particles

Elementary Particles

- Before the quark concepts, all known elementary particles were grouped in four depending on the nature of their interactions

Particle	*Symbol*	*Range of Mass Values*
Photon	γ	$\lesssim 2 \times 10^{-16}$ eV$/c^2$
Leptons	$e^-, \mu^-, \tau^-, \nu_e, \nu_\mu, \nu_\tau$	$\lesssim 3$ eV$/c^2$ – 1.777 GeV$/c^2$
Mesons	$\pi^+, \pi^-, \pi^0, K^+, K^-, K^0,$	
	$\rho^+, \rho^-, \rho^0, \ldots$	135 MeV$/c^2$ – few GeV$/c^2$
Baryons	$p, n, \Lambda^0, \Sigma^+, \Sigma^-, \Sigma^0, \Delta^{++},$	
	$\Delta^0, N^{*0}, Y_1^{*+}, \Omega^-, \ldots$	938 MeV$/c^2$ – few GeV$/c^2$

Elementary Particles

- How do these particles interact??
  - All particles, including photons and neutrinos, participate in gravitational interactions
  - Photons can interact electromagnetically with any particles with electric charge
  - All charged leptons participate in both EM and weak interactions
  - Neutral leptons do not have EM couplings
  - All hadrons (Mesons and baryons) responds to the strong force and appears to participate in all the interactions

Elementary Particles: Bosons and Fermions

- All particles can be classified as bosons or fermions
  - Bosons follow Bose-Einstein statistics
    - Quantum mechanical wave function is symmetric under exchange of any pair of bosons

$$\Psi_B(x_1, x_2, x_3, \ldots x_i \ldots x_n) = \Psi_B(x_2, x_1, x_3, \ldots x_i \ldots x_n)$$

    - x_i: space-time coordinates and internal quantum numbers of particle i
  - Fermions obey Fermi-Dirac statistics
    - Quantum mechanical wave function is anti-symmetric under exchange of any pair of Fermions

$$\Psi_F(x_1, x_2, x_3, \ldots x_i \ldots x_n) = -\Psi_F(x_2, x_1, x_3, \ldots x_i \ldots x_n)$$

    - Pauli exclusion principle is built into the wave function
      - For xi=xj, $\Psi_F = -\Psi_F$

Bosons, Fermions, Particles and Antiparticles

- Bosons
  - All have integer spin angular momentum
  - All mesons are bosons
- Fermions
  - All have half integer spin angular momentum
  - All leptons and baryons are fermions
- All particles have anti-particles
  - What are anti-particles?
    - Particles that has same mass as particles but with opposite quantum numbers
  - What is the anti-particle of
    - A π^0?
    - A neutron?
    - A K^0?
    - A Neutrinos?

Quantum Numbers

- When can an interaction occur?
  - If it is kinematically allowed
  - If it does not violate any recognized conservation laws
    - Eg. A reaction that violates charge conservation will not occur
  - In order to deduce conservation laws, a full theoretical understanding of forces are necessary
- Since we do not have full theory for all the forces
  - Many of general conservation rules for particles are based on experiments
- One of the clearest conservation is the lepton number conservation
  - While photon and meson numbers are not conserved

Baryon Numbers

- Can the decay $p \to e^{+} + \pi^{0}$ occur?
  - Kinematically??
    - Yes, proton mass is a lot larger than the sum of the two masses
  - Electrical charge?
    - Yes, it is conserved
- But this decay does not occur ($<10^{-40}$/sec)
  - Why?
    - Must be a conservation law that prohibits this decay
  - What could it be?
    - An additive and conserved quantum number, Baryon number (B)
    - All baryons have B=1
    - Anti-baryons? (B=-1)
    - Photons, leptons and mesons have B=0
- Since proton is the lightest baryon, it does not decay.

Assignments

1. Carry out Fourier transformation and derive equations 9.3 and 9.5
2. Due is next Wednesday, Mar. 30