Truth and Beauty

and the Physics of the Dark

Robert Kehoe
U. Of Oklahoma
Physics Dept. Colloquium
Sep. 3, 2009
forces of nature

Greece (atomism)
India (vaisesika)
China

building blocks of matter

Zulu (amandala)
Yoruba

Maya
Lakota
Hopi

structure of time and space
• Let’s apply these questions to matter

• We’ll get three more specific questions
  – Why is most of universe ‘dark’?
  – Is our hunch on the origin of mass correct?
  – Why is there any matter in the universe, anyway!??
What is the Matter?
Our ideas of Mass

- Inertial mass
  - A measure of how hard it is to move something, or change its motion

  \[ F = ma \]

- Relativity:
  - Mass as energy?

  \[ E = mc^2 \]
Comprise heavy subatomic particles

Why does nature need these?

In cosmic rays
Antimatter

• Every particle has partner with opposite properties

Can you find the particle-antiparticle pair?
Gravity and Mass

- Mass seems to be the ‘charge’ of gravity

Gravity weaker with increasing distance

Keplerian motion:

Once outside of mass distribution, velocity decrease
Galactic Rotation

Very non-Keplerian
Dark matter
Most matter unidentified!
How is there Mass?
Fundamental Interactions

- Four ‘forces’ of nature
  - Strong
  - Weak (nuclear forces)
  - Electromagnetic
  - Gravity

- Strong interaction → gives masses of protons, neutrons
- ‘Higgs particle’ → gives masses of exchange particles for weak interaction

Think of two skaters
- one throws heavy ball to another
- thrower looses momentum
- receiver gains momentum

Space, x

Time, t

\[ e^- \rightarrow e^- \rightarrow e^- \rightarrow e^- \rightarrow \gamma \]

Exchange particle

Coupling

Strength

- 1
- 1/100,000
- 1/100
- 1/10^{38}
Baryonic Matter

• **Strong interaction**
  - tightly binds quarks and gluons into composite particles
  - Proton and neutron
    • ‘baryons’
    • stable in a nucleus

• Almost all mass we see is baryonic

\[ M_\pi \gg m_u + m_{\bar{u}} \]
A more fundamental mechanism

- Lowest energy state
  - Doesn’t correspond to zero mass

- So W/Z have mass!

Higgs particle
Higgs is ‘sticky’

Impedes change in motion of quarks and leptons (i.e. ‘gives’ mass)

- Stickiness termed ‘coupling’
  - Coupling is proportional to particle mass
  - Value for each particle not predicted: it’s just a number
**When and Where is there Mass?**

Chandra and Compton Observatories:
- Observe galaxy cluster collisions
- No evidence of antimatter pockets
Symmetry

- Charge
- Parity
- physics ‘invariant’ when change these properties
  - CP product a stronger symmetry than C or P alone

... but CP Violation in weak interactions discovered!

\[ K^0 (s\bar{d}) \xrightarrow{\text{time}} \bar{K}^0 (\bar{s}d) \]

This process allows to determine: can start with one CP value, and end up with another one!
Third Generation

- In 1973
  - If there exists a 3rd generation of quarks and leptons...

...this can accommodate CP violation

In 1976:

"We have discovered 64 events of the form

\[ e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{at least 2 undetected particles} \]

for which we have no conventional explanation."

Problem is, observed level of CP violation can’t explain matter over antimatter.
To summarize...

What is the nature or origin of dark matter?

Does the Higgs particle exist?

Why is there only matter, and no antimatter, in the universe?
• 6.1 fb\(^{-1}\) recorded, up to 3.6 fb\(^{-1}\) has been analyzed
  • ~92% operating efficiency for D0

Projections:
- 2010 run: to 10 fb\(^{-1}\)
- 2011 run: to 12 fb\(^{-1}\)
“Chance favors the prepared mind.”
Louis Pasteur
“The scientist ... studies [nature] because he takes pleasure in it; and he takes pleasure in it because it is beautiful.”

H. Poincare

“The measure in which science falls short of art is the measure in which it is incomplete as science.”

J. Sullivan, in Athenaeum (1919)

bottom quark discovered, 1977
A new testing ground

- Particles comprised of $b$-quarks
  - Very analogous to $K^0$

\[
\begin{align*}
B_s^0(\bar{b}s) & \quad \xrightarrow{\text{time}} \quad \bar{B}_s^0(\bar{b}s)
\end{align*}
\]

- Standard model: mass $\neq$ weak eigenstates

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

- Small value of CP phase expected:

\[
\phi_s = 4.2 \pm 1.4 \times 10^{-3}
\]

A. Lenz, U. Nierste hep-ph/0612167

- Measure the CP violating parameter after 5 years of data-taking
• $b \rightarrow c\bar{c} s \rightarrow$ CP even and CP odd final states
  - Separate with time-dependent angular distributions
    - measurement of lifetime difference
  - Large lifetime difference: can extract mixing phase

$A_0$ $A_{1/2}$

Even waves

$A_{1/2}$

Odd waves

1967±65 $B_s$ signal candidates
CDF and D0 Combination
- With systematics
  - $\beta_s \sim -0.5 \phi_s$
    - $[0.27, 0.59] \cup [0.97, 1.30]$ @ 68% CL
    - $[0.10, 1.42]$ @ 95% CL
    - P-value 2.0% (2.33$\sigma$)
What might this mean?

• There are extra particles we have not already identified
  – our calculations are incomplete
  – should include effects from, say, a 4th generation of fermions

• There may be a new symmetry (and interaction)
  – One candidate (called ‘supersymmetry’) also gives us dark matter!
- Alias: ‘top quark’
- Firmly predicted

Discovery 1995
Observing the Top Quark

- Production:

\[ \sigma(\bar{t}t) \approx 7 \text{ pb} \]

- Decays \((\text{BR}(t \to Wb) \sim 100\%)
  - \(W\) and \(b\) decays specify final states
  - Dilepton: two isolated, high \(P_T\) leptons
  - \(L+jets\): one lepton from one \(W\)
  - Leptonic channels analyzed in tagged and untagged modes
  - All-jets: must be \(b\)-tagged to control BG's

\( q \quad g \quad t \quad \bar{q} \quad g \quad \bar{t} \quad g \quad t \quad g \quad \bar{t} \)
Why measure mass?

- EWSB
  - Relation of Higgs mass to top
  - Coupling to fermions not predicted
- Always clues in mass spectrum
  - periodic table
  - Hadrons
  - Fermions?

\[ Y_t = m_t \sqrt{2} / v \ (\sim 1?) \]

Radiative corrections for \( M_W \) go as \( m_t^2, \log(m_H) \)
Undetected neutrinos

2 b-jets

two electrons
Top Dilepton Events

- Low branching ratio (5% for e, \(\mu\))

- Low background
  - Primarily Z
  - Diboson
  - Instrumental

- Explicit channels:
  - \(ee, \mu\mu, e\mu\)

- Implicit channels: b-tagged
  - \(e+\text{track}, \mu+\text{track}\)
  - Need to b-tag to control backgrounds
    - Jet probability tagger
Dilepton Event Characterization

- final state defined by 4-vectors of 6 decay products
  - 18 independent quantities
  - measure 14 directly: lepton and jet momenta, missing Ex and Ey
  - 3 constraints:
    - l-nu pairs give $M_w$
    - $m_t = m_{t\bar{t}}$
    - still have -1C fit!

- sample expected neutrino eta-distribution
Results

Channel $\nu WT_h$ [GeV]

<table>
<thead>
<tr>
<th>2$\ell$</th>
<th>177.5 ± 5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell$+track</td>
<td>170.7 ± 12.3</td>
</tr>
<tr>
<td>combined</td>
<td>176.3 ± 4.9</td>
</tr>
</tbody>
</table>

$m_t = 176.2 \pm 4.8\,(\text{stat}) \pm 2.1\,(\text{syst})$ GeV

- In 10 fb$^{-1}$:
  - 1.4 GeV stat. uncert.
  - 1.3% total uncert. in dilepton channel alone!
New World Average Top Mass

- Combination of all CDF results:
  - Runs I and II
  - Dilepton, l+jets, all-jets

\[ m_t = 172.6 \pm 0.9\text{(stat)} \pm 1.2\text{(syst)} \text{ GeV (CDF)} \]

CDF-NOTE-9714

- Combination of all D0 results
  - Runs I and II
  - Dilepton, l+jets

\[ m_t = 174.2 \pm 0.9\text{(stat)} \pm 1.5\text{(syst)} \text{ GeV(D0)} \]

D0-CONF-5900

New Tevatron March ‘09 combined Mass
FERMILAB-TM-2427-E
arXiv:0903.2503
Heavier than an entire Gold atom!
Electroweak Fits

- Update of Tevatron top mass (+ Higgs exclusion) incorporated:

\[ m_H = 87^{+35}_{-26} \text{ GeV} \]
• Mass proportional to ‘coupling’ to Higgs 
  - For electron: $= 2.9 \times 10^{-6}$
  - For top: $= 0.995 \pm 0.007$
  - Topcolor? 

$\approx 1.0$ to within 0.7%! 

Higgs \[\begin{array}{c}
\text{Higgs} \\
\end{array}\]

\[\begin{array}{c}
top \\
\text{top} \\
\text{Higgs} \\
\end{array}\]
Final thoughts

• May know answer to electroweak symmetry breaking (mass generation) soon

• Will CP violation match electroweak expectation? Will be measured well at LHC

• Is the top quark fundamental?

Hints of new physics?