Experimental Particles Physics:
Search for the Origin of Mass and Matter

Andrei Gritsan

Johns Hopkins University

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Graduate Student Seminar
Experimental High Energy Physics Group at Johns Hopkins

- Who we are
- What we are doing
- Why we are doing this
- How we do this
- Where you can contribute
Experimental High Energy Physics Group

- Experimental HEP faculty at JHU:
  - Bruce Barnett (CDF and CMS)
  - Barry Blumenfeld (CDF and CMS)
  - Chih-Yung Chien (CMS)
  - Andrei Gritsan ($\text{BABAR}$ and CMS)
  - Petar Maksimovic (CDF and CMS)
  - Morris Swartz (CMS)

- CDF experiment at proton-antiproton collider at Fermilab
- $\text{BABAR}$ experiment at electron-positron collider at Stanford
- CMS near-future experiment at proton-proton collider in Europe
Experimental High Energy Physics Group

- Postdoctoral researchers:
  
  Satyajit Behari  \((CDF, \text{ at Fermilab})\)
  
  Zijin Guo  \((BABar, \text{ in Bloomberg})\)
  
  Dongwook Kim  \((CMS, \text{ at Fermilab})\)

- Graduate students:
  
  Yanyan Gao  \((BABar, \text{ in Bloomberg})\)
  
  Mark Mathis  \((CDF, \text{ in Bloomberg})\)
  
  Reid Mumford  \((CDF, \text{ at Fermilab})\)
  
  Jennifer Pursley  \((CDF, \text{ at Fermilab})\)

- expect new people to join
What We Know about Matter

Structure within the Atom

Quark
Size < 10^{-19} m

Electron
Size < 10^{-18} m

Neutron and Proton
Size = 10^{-15} m

Atom
Size = 10^{-10} m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
Study the Standard Model of Matter

- Fermions (spin=$\frac{\hbar}{2}$) ⇒ occupy space and constitute matter

\[
\begin{array}{cccc}
\text{matter} & \text{anti-matter} \\
\text{quarks} & \text{leptons} & \text{anti-quarks} & \text{anti-leptons} \\
(d) & (u) & (e) & (\nu_e) \\
(s) & (c) & (\mu) & (\nu_\mu) \\
(b) & (t) & (\tau) & (\nu_\tau) \\
\end{array}
\]

\[
\begin{array}{cccc}
-d & -u & -e & 0 \\
-s & -c & -\mu & -\nu_\mu \\
-b & -t & -\tau & -\nu_\tau \\
\end{array}
\]

- “Forces” (bosons mediate interactions):
  - Electromagnetic ($\gamma$)
  - Weak ($Z^0$, $W^{\pm}$)
  - Strong (gluons)
  - Gravity (not in model yet...)
Composition of the Cosmos

- Dark Energy: ~70%
- Dark Matter: ~25%
- Heavy elements: 0.03%
- Neutrinos: 0.3%
- Stars: 0.5%
- Free hydrogen and helium: 4%
- Dark matter: ~25%
- Dark energy: ~70%

Antimatter: 0%
Standard Model of Interactions

- Weak
  \[ d \xrightarrow{W^-} d' \]
  \[ d' \xrightarrow{W^+} d \]

- EM (photon)
  \[ d \xrightarrow{\gamma} d \]

- Strong (gluon)
  \[ d \xrightarrow{g} d \]

- Weak interactions are special:
  1. change of quark “flavor” (e.g. \( b \xrightarrow{} u \))
     \[ |d'\rangle = V_{ud} \cdot |d\rangle + V_{us} \cdot |s\rangle + V_{ub} \cdot |b\rangle \]
  2. couple “left-handed” fermions
     helicity \( \lambda = \text{spin-direction} = -\frac{1}{2} \)

- Violate Charge and Parity symmetry
  might violate CP (?)
Fundamental Symmetries

- Symmetries ⇒ conservation laws

\( C \)harge + \( P \)arity (mirror) transformation

Matter \( \leftrightarrow \) Antimatter

- \( CP \) asymmetry \( \leftrightarrow \) matter and antimatter difference
Look Beyond the “Standard Model”

- Why does MATTER dominate (Sakharov):
  - $CP$-asymmetry
  - baryon non-conservation
  - non-equilibrium

- Need something beyond the SM
  - large $CP$-asymmetry
  - dark matter ...
  - $Higgs$ and mass hierarchy problem
Higgs Particle and “New Physics”

- “Naive” Standard Model ⇒ massless particles
  
  Higgs mechanism (math operation) ⇒ masses
  
  expect Higgs particle (heavy)

- Divergent Higgs mass
  
  ⇒ cancellation with superpartners

- New Models (e.g. SUperSYmmetry)
  
  quarks (spin=$\frac{1}{2}$) \( \begin{pmatrix} d \\ s \\ b \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix} \)
  
  s-quarks (spin=0) \( \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} \begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \end{pmatrix} \)
  
  heavy →

  bosons (spin=1/0) \( W, Z/H \)

  \( \tilde{\chi}_i^0, \tilde{\chi}_i^\pm \) (spin=$\frac{1}{2}$) (dark matter?)
Access to New Particles

- Brute force: new particles at highest energy (e.g. CMS, CDF)
  (exceed current $E = mc^2 \sim 100$ GeV)

- Virtual production: $\Delta E \Delta t \sim \hbar$ (e.g. $BABAR$ and CDF)
Bound Quarks: Mesons and Baryons

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Producing New Matter

Smash at high energy

\[ E = mc^2 \]

Stanford Linear Accelerator Center
Producing New Matter: Near Future
Detecting Particles

- Example: $B$ meson decay products on $B_{\text{AB}}$ at SLAC
  
  e.g. $B^0 \to \phi K^0 \to (K^+K^-)(\pi^+\pi^-)$

- Different detector subsystems
Detecting Particles at CMS

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Dashed Green: Neutral Hadron (e.g., Neutron)
- Dark Green: Photon

Chamber Types:
- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid
- Iron return yoke interspersed with Muon chambers
How It Looks: CDF Experiment
BABar Silicon Vertex Detector Assembly

L5a complete
4 Feb 99
b2265
Modern Tracking Detectors

← **CMS** tracker

(>20,000 sensors)

↓ **BABAR** silicon

(340 sensors, R~15cm)
Example: CMS Forward Pixel Detector

- CMS Forward Pixel (optical survey at Fermilab):
  - 3 or 4 sensors on a panel
  - 2 panels back-to-back in a blade = 7 sensors
  - 12 blades in a half-disk
  - half-disks in a cylinder, cylinder in CMS
Need Good Vertex Resolution

- Silicon “alignment” with particle tracks
  crucial for precise particle detection: \( \text{BaBar} \) and \( \text{CMS} \)
- Other technical aspects of detector operation
What We Study

- Analysis of decay products:

  at $B_{\text{A}\beta B_{\text{AR}}}$

  at CMS
Example: Angular Measurements

- Quantum Mechanics

\[ \left( \theta_1, \theta_2 \right) \text{ measure amplitudes from their angular dependence:} \]

\[ \frac{d^3 \Gamma}{d \cos \theta_1 d \cos \theta_2 d \Phi} \propto \sum_{m=-1,0,1} A_m \times Y_{1,m}(\theta_1,0) \times Y_{1,-m}(\pi - \theta_2, -\Phi) \left| ^2 \right. \]

\[ \alpha \left\{ \begin{array}{l}
\frac{1}{4} \sin^2 \theta_1 \sin^2 \theta_2 \left( |A_{+1}|^2 + |A_{-1}|^2 \right) + \\
+ \frac{1}{2} \sin^2 \theta_1 \sin^2 \theta_2 \left[ \cos 2\Phi \, \text{Re}(A_{+1}A_{-1}^*) - \sin 2\Phi \, \text{Im}(A_{+1}A_{-1}^*) \right] \\
+ \frac{1}{4} \sin 2\theta_1 \sin 2\theta_2 \left[ \cos \Phi \, \text{Re}(A_{+1}A_0^* + A_{-1}A_0^*) - \sin \Phi \, \text{Im}(A_{+1}A_0^* - A_{-1}A_0^*) \right]
\end{array} \right. \]

\[ \text{transverse} \]

\[ \text{longitudinal} \]

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Example: Polarization Puzzle

Polarization in $B \rightarrow \phi K^*$

expected: $A_0 \gg A_+ \gg A_-$

measured: $A_0 \sim A_\pm$

$$A_0 \sim 1 \quad \gg \quad A_+ \sim \frac{m_V}{m_B} \quad \gg \quad A_- \sim \frac{m_V^2}{m_B^2}$$

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Summary

- **Origin of Matter and Mass:***
  - Why do we have *matter* and no *antimatter* (*CP* violation)?
  - Can we produce *dark matter* in laboratory?
  - What is the *origin of mass* (Higgs)?

- **On-going collider program at JHU:**
  - **CDF** experiment at *proton-antiproton* collider at Fermilab
  - **BABAR** experiment at *electron-positron* collider at Stanford
  - **CMS** new frontier in 2007-2008

- **Various projects:**
  - *silicon detectors*: calibration, alignment, operation, simulation
  - *data analysis*: simulation, computer reconstruction, results
More information (and some graphics in this talk) on particle physics:

http://particleadventure.org/particleadventure/
http://pdg.lbl.gov/
http://www2.slac.stanford.edu/vvc/
http://public.web.cern.ch/Public/Welcome.html
http://www.fnal.gov/