Seeking Clues for the Next Sakata

Matt Strassler
Oct 27, 2011
SAKATA100 at the new KMI
A Very Different World

• In Sakata’s day there were many surprising discoveries
  – New charged leptons, new neutrinos, new hadrons

• The back-and-forth between theory and experiment occurred rapidly
  – Sakata took great advantage!

• Problem for next Sakata: We have been living in a different era
  – Great experimental progress in understanding neutrinos
    • Neutrinos are not so easy to use theoretically (seesaw: $m = Y M^{-1} Y$)
  – Great observational progress learning about cosmology
    • Dark matter unknown, dark energy confusing, both hard to study
  – Great progress constraining /excluding many speculative ideas
    • Absence of clues is not such a useful clue
The First (Real) Year of the LHC

• But fortunately the LHC era is well underway

• Summer 2011 has changed what we know about high-energy physics

  – No Standard Model Higgs above 145 (140? 135?) GeV
    • Expt (CMS & ATLAS together) says not 145-450
    • Theory (precision loop calculations) says not above ~400

  – Nothing like popular version of supersymmetry at TeV scale
    • Jets from high-energy quarks + MET from dark matter neutralinos

  – Nothing obvious wrong with quantum field theory up to 3 - 4 TeV
$H \rightarrow WW$

$H \rightarrow \gamma \gamma$

$H \rightarrow ZZ$

5 times SM cross-section
ATLAS Supersymmetry search
(jets + MET with b tags)
Dijets at ATLAS

No ``Black Holes`` at CMS
The First Summer of the LHC

• LHC era well underway

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  – No Standard Model Higgs above 145 (140? 135?)
    • Expt says not 145-450
    • Theory says not well above 300

  – Nothing like the most popular version of supersymmetry at TeV scale
    • Jets plus missing transverse momentum (“MET”)
      – from high-energy quarks + invisible neutralinos, or similar

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• Nothing in the data as it has been searched so far!!
The First Summer of the LHC

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Last Week’s News:

• Nothing in the data as it has been searched so far!!
CMS Tri-lepton Events

- Small excess -- not significant, but interesting
- Something to keep an eye on – at this point, nothing more

Plots taken from Richard Grey’s talk at last week’s Berkeley SUSY Workshop

$ST =$ scalar sum of $p_T$ of leptons, jets and missing transverse momentum
Reminder of the LHC and its Experiments

• 3.5 TeV per beam

• Integrated Luminosity
  – \( \sim 35 \text{ pb}^{-1} \) last year per experiment
    • Z cross section is few thousand pb, top cross section 160 pb
    • Higgs/SUSY cross section is 10 pb or lower
  
  – 1000 pb\(^{-1} = 1 \text{ fb}^{-1} \) March – July, \( \sim 2 \text{ fb}^{-1} \) by August
    • (most available results are 1 fb\(^{-1} \) of data)
  
  – \( \sim 5 \text{ fb}^{-1} \) by end October (end of 2011 pp run)

• Pileup: dozens of pp collisions each time two proton bunches cross
• Trigger: thresholds for selecting events to store are rising dramatically
Two Topics

• Flavor Physics: Testing the Predicted Physics of Quarks
  – Standard Model predicts small forward-backward asymmetries
  – Tevatron observes larger top quark forward-backward asymmetry
  – ???

• The Potentially Unexpected: Searching for Hidden Valleys
  – A hidden sector with lightweight particles and a mass gap
  – These can alter expected signals for new physics
Quark-Antiquark Asymmetries at Tevatron and LHC
Tevatron Top-quark Forward-Backward Asymmetry

• proton + anti-proton → top + anti-top

• Since t t-bar is heavy, high-x process
  – gg → t t-bar small
  – q q-bar → t t-bar ; q comes from p, q-bar from p-bar

• Therefore we may ask
  – Does top quark travel in forward direction equally to backward?
    • Forward defined relative to p direction
FORWARD

BACKWARD

usually a quark

top anti-quark

top quark

usually an anti-quark

Proton Beam

Anti-Proton Beam

BACKWARD

FORWARD

usually a quark

top anti-quark

top quark

usually an anti-quark
Therefore we may ask
- Does top quark travel in **forward** direction equally to **backward**?
  - Forward defined relative to $p$ direction

\[
A_{FB} = \frac{N(qy > 0) - N(qy < 0)}{N(qy > 0) + N(qy < 0)},
\]

- $q \bar{q} \rightarrow t \bar{t}$ symmetric only at tree-level
  - picks up small asymmetry (6—8 %) at Next-to-Leading-Order (NLO)

- $gg \rightarrow t \bar{t}$ symmetric forward to back
Tevatron Top-quark Forward-Backward Asymmetry

• CDF
  – Asymmetry large, growing with energy
    • Few percent for $m_{tt} < 450$ GeV
    • $47.5 \pm 11\%$ for $m_{tt} > 450$ GeV (\~{}3 sigma) [t t-bar partonic frame]

• DZero
  – Asymmetry moderate, rather flat in energy
    • About 20\% (\~{}2.5 sigma) throughout
Motivation to Look at Other Quarks

- Seems very difficult to accommodate this with SM only

- No one has found an experimental or theoretical error or even a subtlety

- Models to explain this asymmetry must introduce particles that couple to light quarks and to top quarks
  - Generally very ugly,
    - but goal here is not to judge beauty but to falsify with data

- Model classes:
  - Affect $t_R$ only [expect no effect on other quarks]
  - Affect $t_L$ only/also [expect effect on b quark]
  - Affect all up-type quarks [expect effect on c (and u) quark]
Other quarks at Tevatron?

- Claim: can measure 25% b and c-quark asymmetries at the 3 sigma level
- Method:
  - Select dijets
  - Look for muon inside of jet and look at charge asymmetry of the muon

MJS 2/11; cf Hewett et al. 1/11
Dijet Plus Embedded Muon

charm quark
bottom anti-quark

charm anti-quark
bottom quark

Dilution Effects
bottom quark can produce an anti-lepton

B B mixing
Other quarks at Tevatron?

- Claim: can measure 25% b and c-quark asymmetries at the 3 sigma level

- Method:
  - Select dijets
  - Look for muon inside of jet
    - Hadronic sources: B meson decay, D meson decay
    - Partonic sources: b, c → c, g → c c-bar, g → b b-bar
  - Look for forward-backward asymmetry of anti-muons (in dijet frame)
  - Combine with backward-forward asymmetry of muons
  - Use b-tagging, muon kinematics to
    - Isolate b asymmetry from c asymmetry
    - Reduce dilution of b asymmetry from B → B-bar, B → D
# Dijet Plus Embedded Muon

Jet $p_T > 150$ GeV [dijet trigger]
$M_{jj} > 450$ GeV
Muon $p_T > 20$ GeV, $|\eta| < 2$

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<th>Cross-section</th>
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<td>Light quarks and gluons</td>
<td>$1.0$ pb (0.25 with gg final states)</td>
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<td>Charm pairs</td>
<td>$0.15$ pb</td>
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<td>$0.3$ pb</td>
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<tr>
<td>Total</td>
<td>$1.8$ pb</td>
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1500 events
3000 events
18000 events

Despite large b-bbar cross-section, dilution factor of 3 reduces sensitivity below charm:

- $b \rightarrow c \rightarrow \mu$ with wrong sign
- $B \rightarrow \bar{B}$-bar $\rightarrow \mu$ with wrong sign
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$B \rightarrow B$-bar $\rightarrow \mu$ with wrong sign

- b-tag muon-free jet
- Higher jet $p_T$ cut
- Higher muon $p_T$ cut
- Muon relative-$p_T$ cut
• Cannot measure forward backward asymmetries
• Can measure more-forward/more-central asymmetries
  – Boost direction of the event indicates the q direction statistically

\[ A_{FC}^{b\bar{b}} = \frac{N(q\Delta|y| > 0) - N(q\Delta|y| < 0)}{N(q\Delta|y| > 0) + N(q\Delta|y| < 0)}, \]

Event Boost Direction

Proton Beam

More Forward

More Central

Top Quark

Top Anti-Quark

Usually a Quark

Usually an Anti-Quark

Kahawala, Krohn & MJS 8/12
Jet $p_T > 150 \text{ GeV}, 100 \text{ GeV}$
Muon $p_T > 25 \text{ GeV}, |\eta| < 2.4$ near one jet
b-tag of other jet [no hope without b-tag, so can’t do charm asym]

<table>
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<tr>
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<th>$y_{jj} &gt; 1/2$</th>
<th>$m_{jj} &gt; 450$</th>
</tr>
</thead>
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<tr>
<td>$\sigma_{q\bar{q} \rightarrow b\bar{b}}$ (pb)</td>
<td>1.1</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_{q\bar{q} \rightarrow b\bar{b}}$ (pb)</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>$\sigma_{gg \rightarrow b\bar{b}}$ (pb)</td>
<td>7.1</td>
<td>4.0</td>
<td>0.9</td>
</tr>
<tr>
<td>other background</td>
<td>10.0</td>
<td>5.7</td>
<td>1.6</td>
</tr>
<tr>
<td>$\sigma_{total}$ (pb)</td>
<td>18.6</td>
<td>10.7</td>
<td>2.7</td>
</tr>
<tr>
<td>$A_{FC}^{b\bar{b}}$ (%)</td>
<td>0.6</td>
<td>0.9</td>
<td>1.6</td>
</tr>
<tr>
<td>significance ($\sigma$)</td>
<td>2.5</td>
<td>2.8</td>
<td>2.6</td>
</tr>
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- Numbers for 10 fb$^{-1}$
- Modeled asymmetry in range observed by Tevatron using suitable axigluon model only in that limited range – so probably conservative
- Some improvements possible; vertex location, muon $p_T$, differential asym
- LHCb?
Many models to explain top FB asymmetry produce other types of asymmetries at LHC

For example:

- Shelton-Zurek model excluded (probably) using total charge asymmetry
  - $W'^+ \text{ production} > W'^- \text{ production}$

- Many other models excludable soon with differential charge asymmetries
  - New particle reconstructed-mass plot shows asymms

Test Asymmetries With Asymmetries
Impact of Hidden Valleys on LHC Searches
Current Main Search Strategies at LHC

- Higgs Boson searches
- SUSY-like
  - High energy jets
  - Large missing transverse momentum
  - Perhaps add something rare (b-tag, lepton, photon)
- Exotic-classes
  - New resonances
    - produced singly or doubly
    - Decaying to 1, 2, or perhaps 3 leptons/photons/jets
- Black Holes
  - Huge energy, large number of jets etc.
- A few other specific cases
Signals Can be Hidden by Hidden Valleys

- A hidden sector that produces a visible signal can cause problems
  - Higgs boson can become very hard to find
  - SUSY etc. can be harder to detect
  - Black holes can look very different from expectations

- It can also provide new but exotic opportunities to discover them

- So far very few dedicated analyses searching for this possibility
Hidden Valley Scenario (w/ K. Zurek)

- Not a model, but a scenario:
  - A Very Large Meta-Class of Models

Basic minimal structure:

- **Standard Model**: SU(3)xSU(2)xU(1)
- **Communicator**
- **Hidden Valley**: $G_v$ with v-matter

[hep-ph/0604261]
A Conceptual Diagram

Energy

Entry into Valley via Narrow “Portal”

Multiparticle Production in Valley

Some Particles Unable to Decay Within Valley

Slow Decay Back to SM Sector via Narrow Portal

Inaccessibility

LHC

LEP

SM
Analogy: QCD
Production through Z decay

- New lightweight resonances
- Some long-lived resonances
- Multiparticle production with unusual clustering
EXAMPLE: Confining Hidden Valley Production through Resonance Decay

- New neutral lightweight resonances
- Some long-lived resonances
- Multi-particle production with unusual clustering

Some v-hadrons are stable and therefore invisible

But some v-hadrons decay, to bb pairs, qq pairs, lepton pairs, etc.

Analogous to e+e- → hadrons
Common Predictions of HV Scenario

- Possible big effect on Higgs
  - $H \rightarrow XX, X$ decays displaced $\Rightarrow$ new discovery mode
    - *not unique to HV* Chang Fox Weiner 05 / Carpenter Kaplan Rhee 06
  - $H \rightarrow XXX, XXXX, etc$
    - *not unique to HV*

- Big effect on Supersymmetry, UED, Little Higgs – any theory w/ new global charge
  - LSP (or LKP or LTP) of our sector can decay to the valley LSP/LKP/LTP

Generalizes well known work from 90s
- [GMSB, Anomaly, Hidden Sector]

Higgs can decay in way that causes problems for trigger and for analysis

Classic MET signal of SUSY and similar models can be reduced
hep-ph/0604261
hep-ph/0605193

Possibly displaced vertex

g

h

h_v

Possibly displaced vertex

mixing

v-particles
The traditional missing energy signal is replaced with multiple soft jets, reduced missing energy, and possibly multiple displaced vertices.
Reduction of Missing Energy Signal

Distribution of Missing Transverse Energy

Need for Additional Search Strategies at LHC
Lisanti, Schuster, MJS & Toro

Black is CMS data
Red is MSUGRA model
Hidden Valley between Blue and Green curves
Many other examples...

It is probably time to broaden search strategies to assure a hidden valley has not hidden the Higgs, SUSY, extra dimensions, or other new phenomena from the standard search strategies.

4 taus in every SUSY event, 2 possibly displaced, plus soft v-particles, possibly with displaced decays.
Summary

• Exciting new era with great potential for a quick-minded brilliant theorist

• Surprising top forward-backward asymmetry
  – Important to measure this for other quarks – seems possible
  – Models to explain it can generate large charge asymmetries at LHC

• Remember signals can hide in presence of hidden valley
  – Current trigger not likely to fire on many exotic Higgs decay modes
  – Missing Transverse Momentum signals often reduced
  – Since obvious searches have not seen anything, soon need to start looking seriously for this wide range of possibilities

• Looking forward to broader and deeper analysis of LHC data!
Additional Slides
Proton Beam  

usually a quark  

top anti-quark  

Event Boost Direction  

MORE FORWARD  

MORE CENTRAL  

usually an anti-quark  

top quark  

top anti-quark  

Proton Beam
Recent Hidden Valleys in Literature

• Unparticles [conformal hidden sector] Georgi 07– no mass gap
  – Mainly invisible

• But many papers (07) break conformal invariance and generate mass gap
  – Hidden sector now becomes hidden valley
    • Cannot use conformal methods (though many papers did)
    – Correct physics is either invisible or hidden-valley-like (MJS 2008)

• Hidden dark-matter sectors to explain PAMELA [Arkani-Hamed et al. 09]
  – Lepton-jets (clustered boosted resonances decaying to leptons)
  – Can affect Higgs/SUSY decays
HV Higgs Scenarios

- $H \rightarrow XX$, $X$ decays to
  - Mostly $b$ quarks, occasional taus
  - Mostly quarks, occasional leptons
  - Mostly gluons, occasional photons

  Will the trigger even fire under current conditions?!

- $H \rightarrow XXXX$ ; triggering?!!?!?

- $H \rightarrow XX$, $X$ decays with displaced vertex
  - Trigger a serious impediment
  - ATLAS: long-lived particle search (trigger on muon 40 GeV)
  - CMS: $X \rightarrow$ displaced leptons only sensitive to $m_H > 200$ GeV
    - due to trigger efficiency