Searching for Hidden Valleys and Warped Throats at the LHC

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Summary

Part I:
- Hidden Valleys
  - An overview (Strassler, KZ, hep-ph/0605193,0604261)
- Hidden Valleys at hadron colliders
  - Search strategies (Han, Si, KZ, to appear)
- Hidden Valley model building: motivating hidden valleys from warped throats (Shiu, KZ, in progress)

Part II:
- Warped extra dimensions from warped string compactifications (Shiu, Underwood, Walker, KZ, 0705.4097)
  - Fluxes to stabilize moduli lead to warped throats
  - Look like 10-d relatives of Randall-Sundrum, but with different IR behavior of warping (Klebanov-Strassler throat)
  - Important implications for RS model building and phenomenology
A hidden valley: what is it?

Generic structure of hidden sectors:

- Communicator
- Standard Model
- Hidden Sector
A hidden valley: what is it?

Generic structure of hidden sectors:

- Gravity
- Standard Model
- SUSY breaking sector with auxiliary fields
A hidden valley: what is it?

Generic structure of hidden sectors:

- Gauge fields, messenger quarks, messenger fermions

- Standard Model

- Singlet field breaking SUSY of messenger fields
A hidden valley: what is it?

Generic structure of hidden sectors:

- Higgs
- Standard Model
- Copy of Standard Model
- Mirror sector
- $Z_2$ symmetry

“Twin Higgs”, Chacko, Goh, Harnik
A hidden valley: what is it?

Generics structure of hidden sectors:

Standard Model

Scalars to hide Higgs decays

$h \rightarrow 2\phi \rightarrow 4b, 4\tau$

Chang, Fox, Weiner

$h \rightarrow 2a$ NMSSM

Dermisek and Gunion, “E-sectors”
A hidden valley: what is it?

Generic structure of hidden sectors:

**Higgs, Gauge Particles**

- Standard Model
- Conformal Sector, “Unparticles”

\[ \frac{1}{M^k_U} O_{SM} O_{BZ} \]

Georgi, 2007
A hidden valley: what is it?

Key feature:

Confinement, Low-mass hadrons

TeV Mass Mediator

Standard Model

v-quarks, SU(N)

V is for Valley

V-confinement

V-hadrons
Imagery

- LHC
- Tevatron
- LEP

Energy

Standard Model

V-sector
As opposed to:

- Standard Model
- LHC
- Tevatron
- LEP
- Higgs sector
- MSSM particles
- KK modes
- High mass peaks
Bottom-up

- Novel phenomenology for which there currently are no searches
  - Low mass hidden sectors
    - Displaced vertices
    - High multiplicities
    - Low mass resonances
  - Specific model to determine signatures
    - $U(1)_X$ with $Z'$ mediator, single low mass quark
  - Broad class of models which generate?
    - Top-down inspired models
    - Warped hidden valleys
Confinement in Hidden Sector

$Z'$ mediator

$v$-quarks

$v$-gluons

$V$-confinement producing shower of $v$-hadrons
V-hadron decays

Potentially light $v$-sector

$\Gamma_{\eta_v \rightarrow b\bar{b}} \sim 6 \times 10^9 \text{ s}^{-1} \frac{f_{\eta_v}^2 m_{\eta_v}^5}{(20 \text{ GeV})^7} \left(\frac{10 \text{ TeV}}{m_{Z'} / g'}\right)^4$

$\Gamma_{\rho_v \rightarrow l\bar{l}} \sim 4 \times 10^{18} \text{ s}^{-1} \frac{m_{\rho_v}^5}{(20 \text{ GeV})^5} \left(\frac{10 \text{ TeV}}{m_{Z'} / g'}\right)^4$
Looking for displaced vertices

- Previously, there was no generalized displaced vertex search
  - “Experimentalists are used to looking for displaced vertices”
    - True, but not
    - B-tagging looks for cm displaced vertex
    - Displaced vertices not typical of b’s are rejected, as they are usually cosmic rays
    - Most usual BSM candidates have prompt decays
      - Notable exceptions: SuperWIMPs, gluinos in split SUSY
Looking for displaced vertices

- Some limited searches as a result:

  \[ b' \rightarrow Z^0 b \quad Z^0 \rightarrow e^+ e^- \quad \text{CDF collaboration, hep-ex/9805017} \]

  \[ \tilde{N} \rightarrow Z^0 + \tilde{G} \quad \rightarrow \mu^+ \mu^- \quad \text{CDF collaboration, hep-ex/0410019} \]

- Atlas WG on displaced vertices (Rome/Seattle collaboration)
  - Studies in beampipe are very mature from experience with b’s
  - Studies on displaced vertices in inner and outer calorimeters under way; reconstruction with level II trigger feasible
Higgs decays with displaced vertices

Mixing is not necessarily small \( \rightarrow \) branching is not necessarily small

Tunneling through \( Z' \) can lead to displaced vertices

Strassler, KZ hep-ph/0604261
Higgs decays with displaced vertices

- Generalize against some existing ideas in the literature

\[ V = \text{mass and quartic terms} + \zeta S^2 H^2 + aS + bS^3 + cSH^2 \]

Dermisek and Gunion; Chang, Fox, Weiner

\[ \Gamma_s \propto c \Rightarrow \text{can be long lifetimes} \]
But if no displaced vertex?

- Challenges:
  - High multiplicities
    - (Lots of stuff in the event)
  - Fairly soft, low mass $v$-hadrons
  - How to distinguish from QCD?

\[ \Gamma_{\eta_c \to b\bar{b}} \sim 6 \times 10^9 \text{ s}^{-1} \frac{f_{\eta_c} m_{\eta_c}^5}{(20 \text{ GeV})^7} \left( \frac{10 \text{ TeV}}{m_{Z'} / g'} \right)^4 \]

\[ \Gamma_{\rho \to \mu^+ \mu^-} \sim 4 \times 10^{18} \text{ s}^{-1} \frac{m_{\rho}^5}{(20 \text{ GeV})^5} \left( \frac{10 \text{ TeV}}{m_{Z'} / g'} \right)^4 \]

Han, Si, Zurek, 2007
Backgrounds can be daunting
Use typical energy scales

- Low mass $v$-hadrons
  - Use displaced vertex

- Higher mass $v$-hadrons
  - Shape of event set by confinement scale

\[
\Gamma_{v \rightarrow b\bar{b}} \sim 6 \times 10^9 \text{ s}^{-1} \frac{f_{\eta_v}^2 m_{\eta_v}^5}{(20 \text{ GeV})^7} \left( \frac{10 \text{ TeV}}{m_Z / g'} \right)^4
\]

Cone size set by confinement scale

\[
\theta \sim \frac{p_\perp}{E_h} \sim \frac{p_\perp}{E_{cm}} N_h, \quad N_h \sim \ln \frac{E_{cm}}{m_h}
\]

Light quark jets:

\[
p_\perp \sim 1 \text{ GeVish}
\]
Used in b-tagging

- Cone size set by b-meson mass
  - B-meson sits in the middle of light quark jets

Two effects contribute:
- Parent v-hadrons more widely separated
- Decay products more widely separated

B-quark jets:
\[ p_\perp \sim 5 \text{ GeV} \]
\[ \theta \sim \frac{m_h}{E_h} \]

Light quark jets:
\[ p_\perp \sim 1 \text{ GeVish} \]
Lego Plot View
Contrast Hidden Valley Events
Characterized by high multiplicities

\[ P(\sigma, N) \]

Han, Si, Zurek, 2007
How to quantify these qualitative features?

- Well separated leptons

Strongest constraints derived from $Z$-$Z'$ mixing at LEP

\[ \Delta R = \sqrt{\left( \Delta \phi \right)^2 + \left( \Delta \eta \right)^2} \]

Han, Si, Zurek, 2007
Best measure: invariant mass of cluster

\[ m_{clus}^2 = \left( \sum E_i \right)^2 - \left( \sum \vec{p}_i \right)^2 \]

Highly collinear \( \rightarrow \) low invariant mass

Han, Si, Zurek, 2007
Implement cuts; reconstruct resonance

- At least 2 isolated leptons
  - $p_T > 15$ GeV, $\Delta R > 0.3$
  - $p_T > 10$ GeV, $\Delta R > 0.3$
- Invariant mass cut
  - $M_{\text{cluster}} > 20\% p_T^{\text{cluster}}$
- Reconstruct resonance via invariant mass of lepton pairs

Han, Si, Zurek, 2007
Reconstruct resonance

Han, Si, Zurek, 2007
Bottom-Up to Top-Down

- Have been focusing on bottom-up
  - Broad class of models
    - Many mediators
    - Many possible hidden sectors with different matter content
    - Use specific model as example to demonstrate feasibility of search for broad class of models
  - Missing search techniques
    - Displaced vertices
    - Isolated leptons
    - Fat jets
- How about top-down?
  - Why should we bother looking for these things?
Top-down

- Well-motivated in bottom-up model-building
  - Gauge mediation, gravity mediation, twin Higgs, hidden Higgs decays.....
- Well-motivated in top-down string constructions
  - Lots of extra matter in string theories
  - What generic way can we get a TeV mass mediator?
Multi-throat models

- Multi-throat + warped extra dimensions
  - Result from moduli stabilized by fluxes
  - Can solve the hierarchy problem this way in string theories
  - Naturally get TeV mass graviton mediators
  - TeV communication between SM throat and hidden throats

Cacciapaglia, Csaki, Marandella, Terning

Dimopoulos, Kachru, Kaloper, Lawrence, Silverstein
Two-throat hidden valley model

Standard Model

Throat 1

bulk

Copy of Standard Model

Throat 2

KK graviton communicator
Two-throat hidden valley model

Standard Model

Copy of Standard Model

Throat 1

bulk

Throat 2

KK graviton communicator

Tunneling graviton
Two-throat to multi-throat

Resonance condition must be met to obtain significant tunneling

\[ P = \left( \frac{\left( t + \frac{1}{t} \right) \left( H_2^- H_1^+ - H_1^- H_2^+ \right)}{H_2^{+2} + H_1^{+2} + \left( t - \frac{1}{t} \right) H_2^+ H_1^+} \right)^2 \]

\[ t = \tan ml \]

\[ t - \frac{1}{t} \ll 1 \Rightarrow m \sim l \]

Can obtain band resonance structure from periodic potential

Langfelder, 2006
Or a single throat...

Both SM and Hidden sector must be localized toward TeV brane to get TeV (only) suppressed operators.
Conclusions

- Considered class of hidden sector models with confining gauge group
  - May search with displaced vertices
  - But events also have unique topology
    - Use
      - Isolated leptons
      - Invariant mass of cluster
  - Classes of models
    - Bottom up
      - Z', Higgs mediators, Mirror sectors
    - Top down
      - Warped throats with hidden sectors
Part II: String compactifications and RS phenomenology

Shiu, Underwood, Walker, KZ
0705.4097 (hep-ph)
Warped throats in Randall-Sundrum type solutions to hierarchy

\[ ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2 \]

Metric is sick at large \( y \)

Raman Sundrum's orange slicing analogy:

Truncate space at \( y = \pi r_c \)
In the language of warped throats

\[ ds^2 = e^{-2k_y} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2 \]

\[ ds^2 = f(r)^{-1/2} \eta_{\mu\nu} dx^\mu dx^\nu + f(r)^{1/2} (dr^2 + r^2 d\Omega^2) \]

AdS: \[ f(r) = \frac{R^4}{r^4} \]

Divergent \( r \to 0 \)

Truncate space at \( r_{\text{tip}} \)

\[ r = e^{-k_y} \]

Metrics arising in string theories (from stabilizing moduli with fluxes) often have smooth IR cutoff
Sample string theory metric

Warped deformed conifold or Klebanov-Strassler throat

Asymptotically AdS

\[ ds_{10}^2 = h^{-1/2}(\tau) dx_n dx_n + h^{1/2}(\tau) ds_6^2 \]

\[ ds_6^2 = \frac{1}{2} \tau^{4/3} K(\tau) \left[ \frac{1}{3 K^3(\tau)} (d\tau^2 + (g^3)^2) + \cosh^2 \left( \frac{\tau}{2} \right) [(g^1)^2 + (g^4)^2] \right. \]

\[ + \sinh^2 \left( \frac{\tau}{2} \right) [(g^1)^2 + (g^4)^2] \left. \right] , \]

\[ K(\tau) = \frac{(\sinh(2\tau) - 2\tau)^{1/3}}{2^{1/3} \sinh \tau} . \]

\[ h(\tau) = \frac{2^{2/3}}{4} I(\tau) = (g_s M_\alpha)^2 2^{2/3} \varepsilon^{-8/3} I(\tau) , \]

\[ I(\tau) \equiv \int_{\tau}^{\infty} dx \frac{x \cosh x - 1}{\sinh^2 x} (\sinh(2x) - 2x)^{1/3} . \]
Warped deformed conifold

Singular conifold

\[ ds_6^2 = dr^2 + r^2 ds_{T^{1,1}}^2 \]

Stack of D3-branes at tip

\[ AdS_5 \times T^{1,1} \]

NS-NS and RR fluxes on cycles

Warped deformed conifold
Graviton profiles in extra-dim

In comparison to RS, KS gravitons

• Are more closely spaced in mass

• Have stronger and mode dependent couplings

Shiu, Underwood, Walker, KZ 0705.4097 (hep-ph)
Mode dependent couplings

- In RS, couplings are universal
- In KS, couplings are non-universal, and become stronger with higher KK mode
- Wavefunctions continue to grow in IR
- Normalization and volume factors

\[ V_w \delta_{m,n} = \int d^{D-4}y \sqrt{\tilde{g}} f^{(D-6)/4}(y) \phi_n(y) \phi_m(y) \]

- Oscillation to minimum just volume factor is peaking

\[ V_w = \int d^{D-4}y \sqrt{\tilde{g}} f^{(D-6)/4}(y) \]

\[ L = \frac{1}{M_{pl}} h^{0}_{\mu\nu} T^{\mu\nu} + \frac{1}{\Lambda_{KK}} \sum h^n_{\mu\nu} T^{\mu\nu} \]

\[ \Lambda_{KK} = \frac{M_{pl}}{\phi_n(r_{IR})} \]
Mode dependent couplings

\[ L = \frac{1}{M_{pl}} h_{\mu\nu}^0 T^{\mu\nu} + \frac{1}{\Lambda_{KK}} \sum h_{\mu\nu}^n T^{\mu\nu} \]

\[ \Lambda_{KK} = \frac{M_{pl}}{\phi_n (r_{IR})} \]

<table>
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<th>KK Mode</th>
<th>RS Mass</th>
<th>KS Mass</th>
<th>RS Coupling</th>
<th>KS Coupling</th>
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</table>
Implications for phenomenology
Dominant Production and Decay Depends on Localization

Unknown how to embed SM in string theories; side-step problem by putting all fields on the TeV brane
Observations

Shiu, Underwood, Walker, KZ 0705.4097 (hep-ph)

Narrower spacing and broader peaks at higher KK mode
For model-building purposes, introduce “mass gap” metric

\[ f(r) = \frac{R^4}{r_{tip}^4 + f_2 r_{tip}^2 + r^4} \]

Shiu, Underwood, Walker, KZ
0705.4097 (hep-ph)
Implications for RS-type model building

- Production rates / branching fractions of any field peaked near TeV brane very sensitive to geometry of warped throat
- New model building possibilities
  - Implication for precision electroweak with fields in the bulk?
  - If very sensitive to precise form of the warp factor, how rigorous are constraints on RS models with SM fields in bulk?
  - Use the mass gap metric to parametrize IR modifications of the metric
- Learn about nature of parent string theory through pattern of masses/couplings?
Conclusions

- Hidden valleys yield novel phenomenology, consistent with broad class of models
  - Fat jets, isolated leptons; search could be implemented with triggers already in place
  - Warped throat model for hidden valleys
- Small changes in AdS metric yield big changes in warped extra dimension phenomenology
  - Future: RS model building with string theory metrics