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:

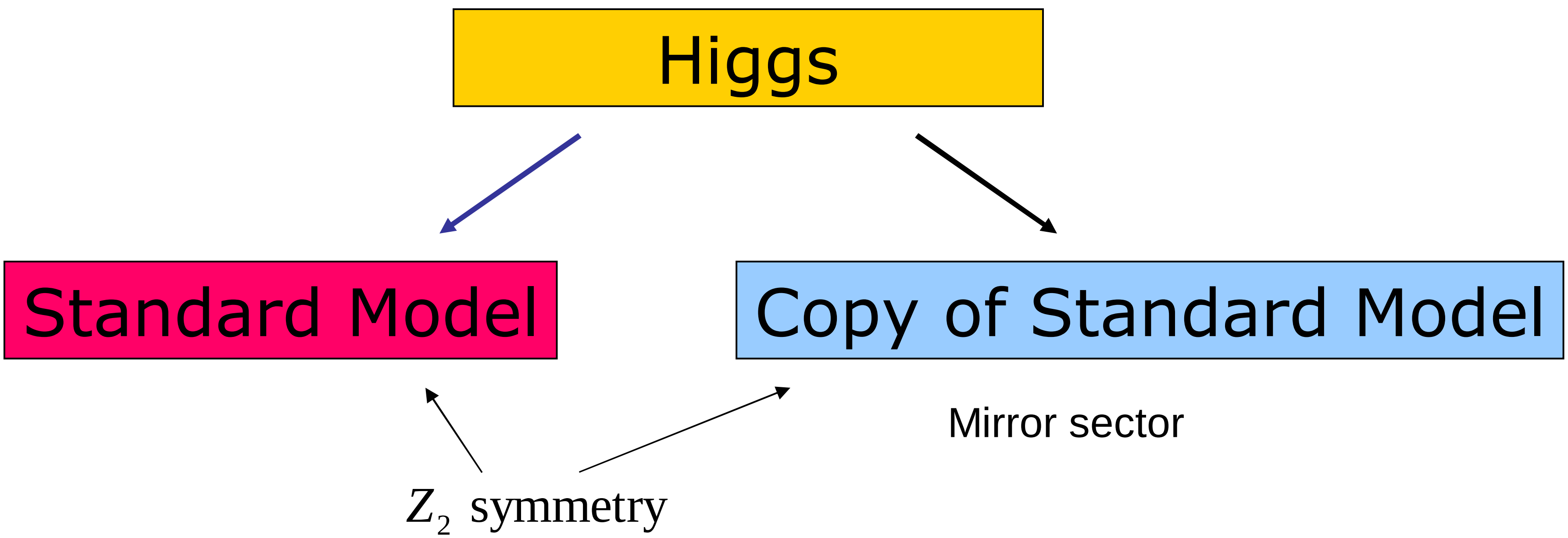
Gauge fields, messenger quarks, messenger fermions

Standard Model

Singlet field breaking SUSY of messenger fields

A hidden valley: what is it?

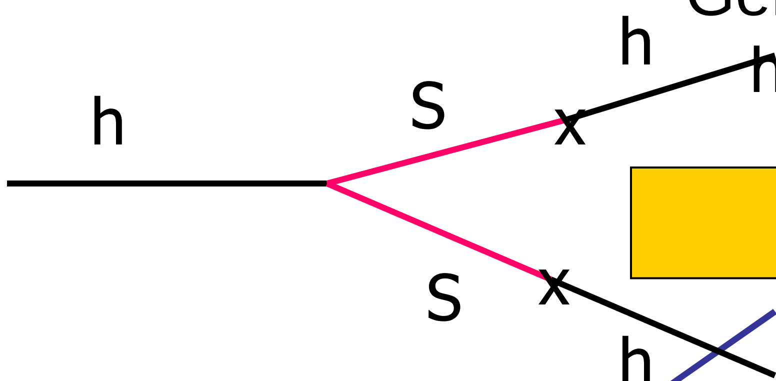
Generic structure of
hidden sectors:



“Twin Higgs”, Chacko, Goh,
Harnik

A hidden valley: what is it?

Generic structure of hidden sectors:



Higgs

Standard Model

Scalars to hide Higgs decays

$h \to 2\phi \to 4b, 4\tau$ Chang, Fox, Weiner

$h \to 2a$ 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"

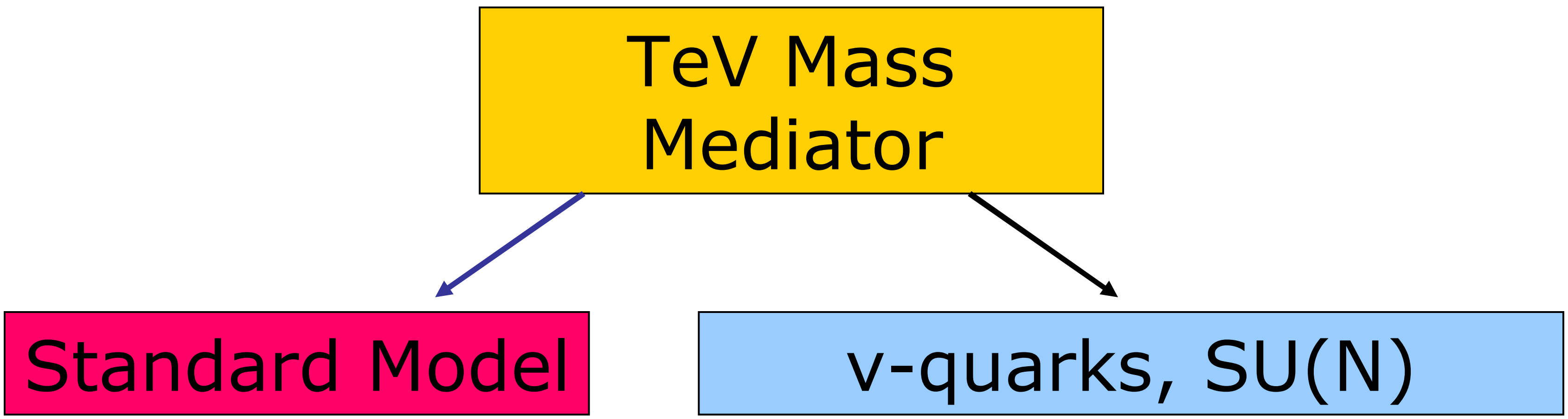
$$\frac{1}{M_U^k} O_{SM} O_{BZ}$$

Georgi, 2007

A hidden valley: what is it?

Key feature:

Confinement, Low-mass hadrons

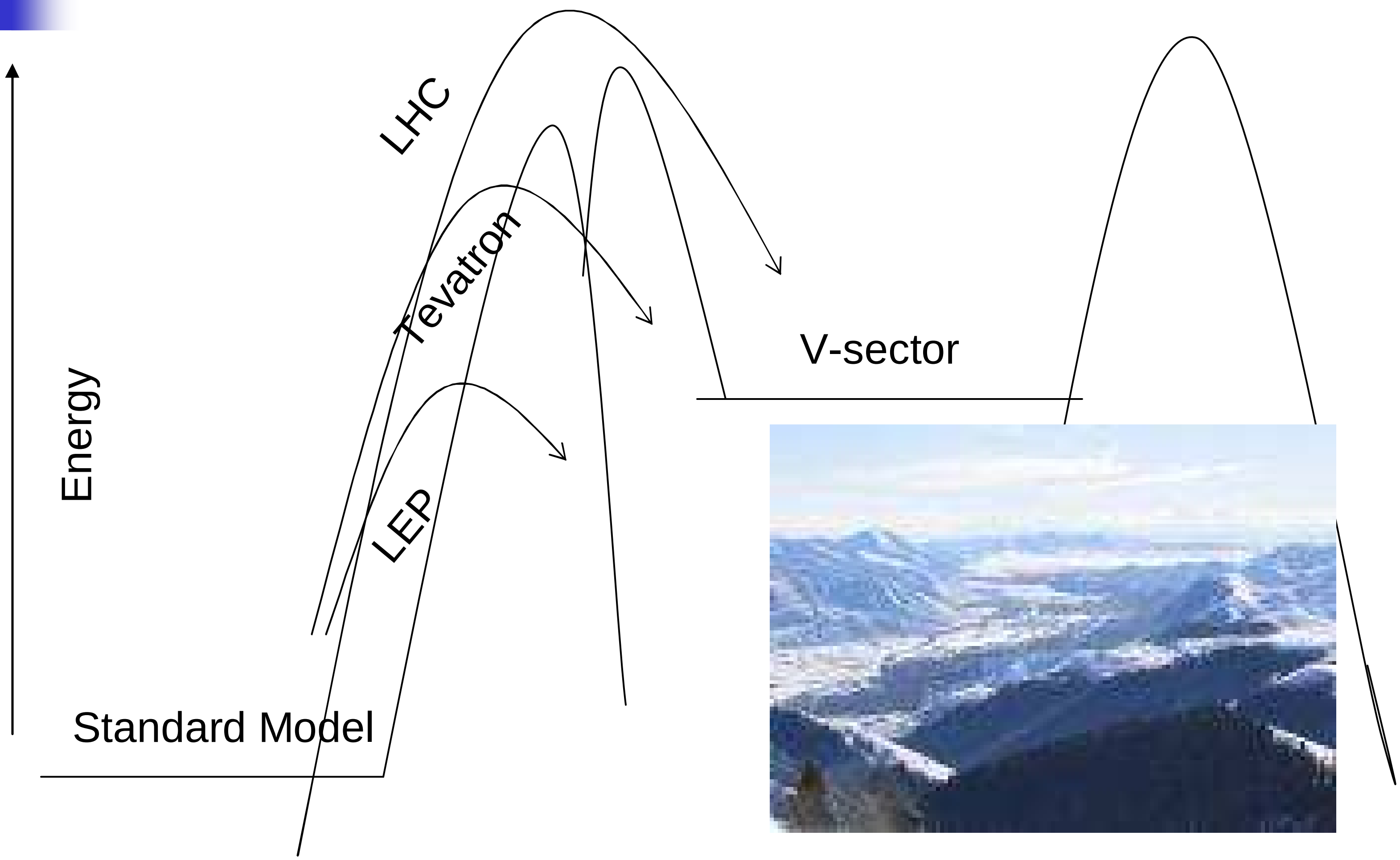


V is for Valley

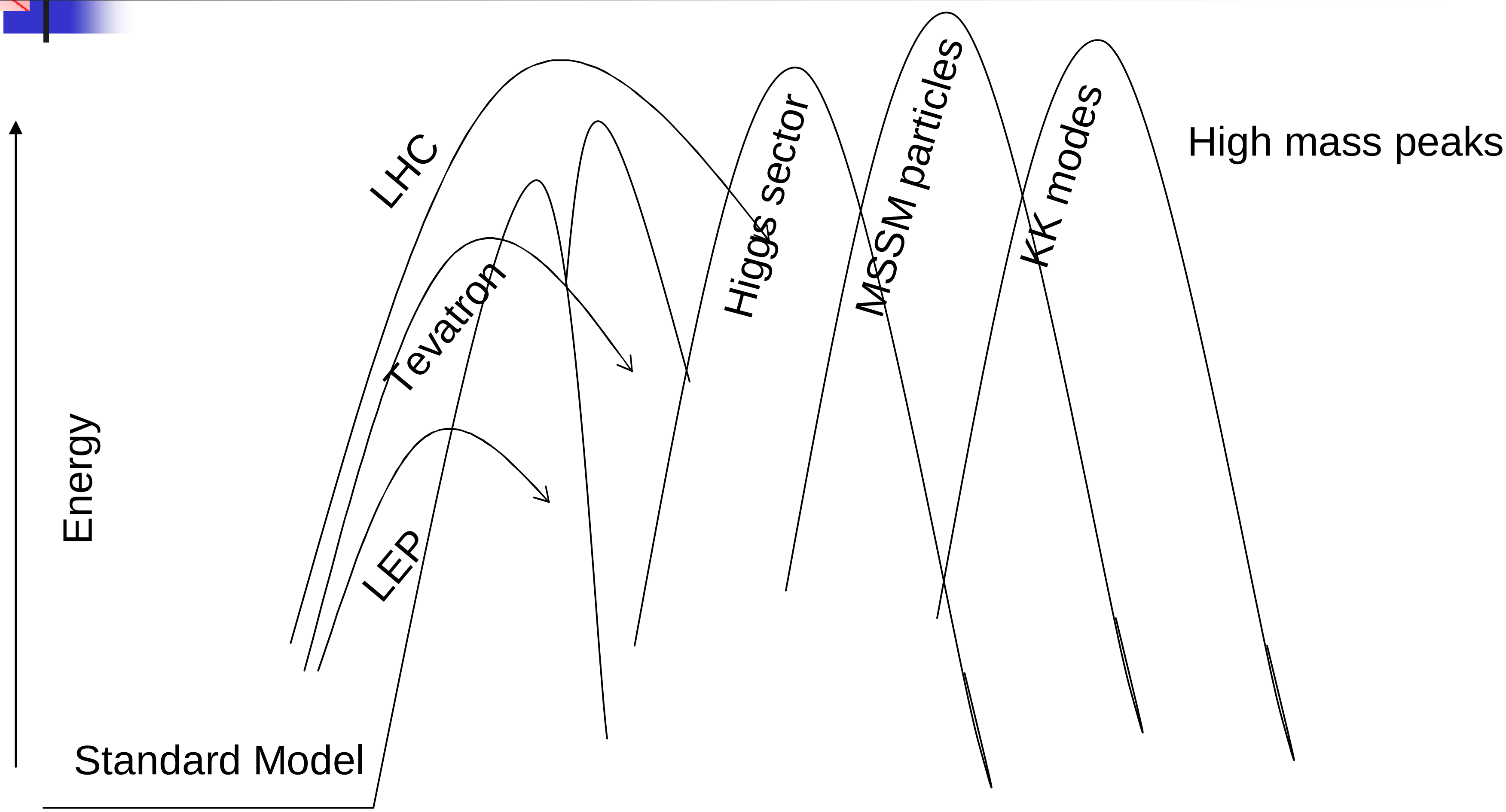
V-confinement

V-hadrons

Imagery



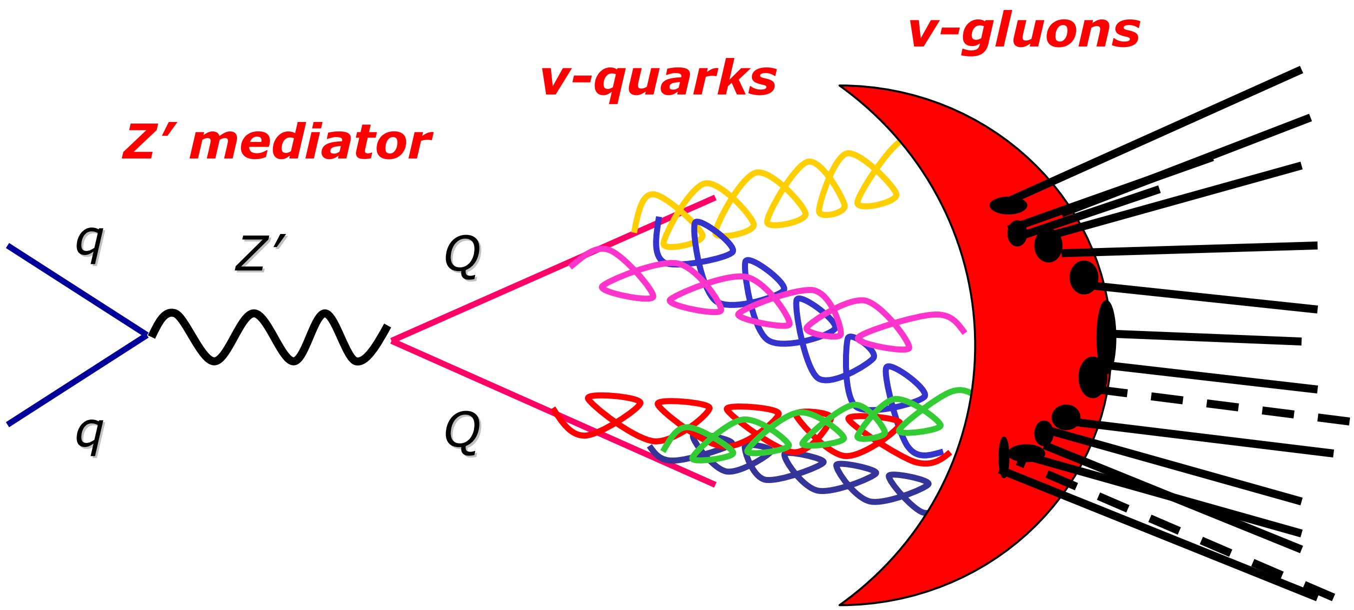
As opposed to:



Bottom-up

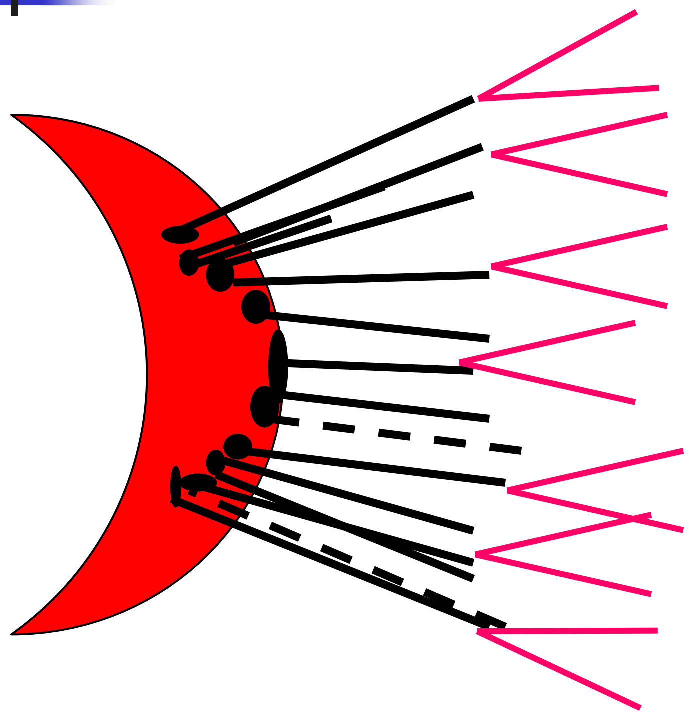
- Novel phenomenology for which there currently are no searches
  - Low mass hidden sectors
    - Displaced vertices
    - High multiplicities
    - Low mass resonances
- Specific model to determine signatures
  - $U(1)_\chi$ with Z′ mediator, single low mas quark
- Broad class of models which generate?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

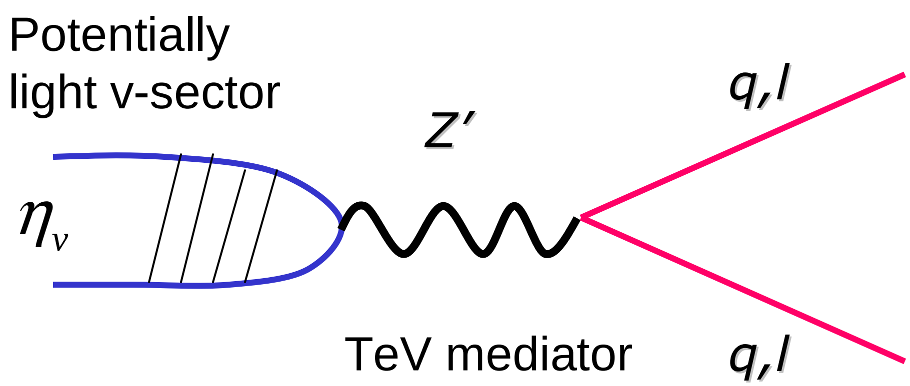
Confinement in Hidden Sector



V-confinement producing shower of v-hadrons

V-hadron decays





$$\Gamma_{\eta_v \to b\bar{b}} \sim 6\times10^{9}\ \mathrm{s}^{-1}\,\frac{f_{\eta_v}^{2} m_{\eta_v}^{5}}{(20\ \mathrm{GeV})^{7}}\left(\frac{10\ \mathrm{TeV}}{\mathrm{m}_{Z'}/g'}\right)^{4}$$

$$\Gamma_{\rho_v \to l\bar{l}} \sim 4\times10^{18}\ \mathrm{s}^{-1}\,\frac{m_{\rho_v}^{5}}{(20\ \mathrm{GeV})^{5}}\left(\frac{10\ \mathrm{TeV}}{\mathrm{m}_{Z'}/g'}\right)^{4}$$

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

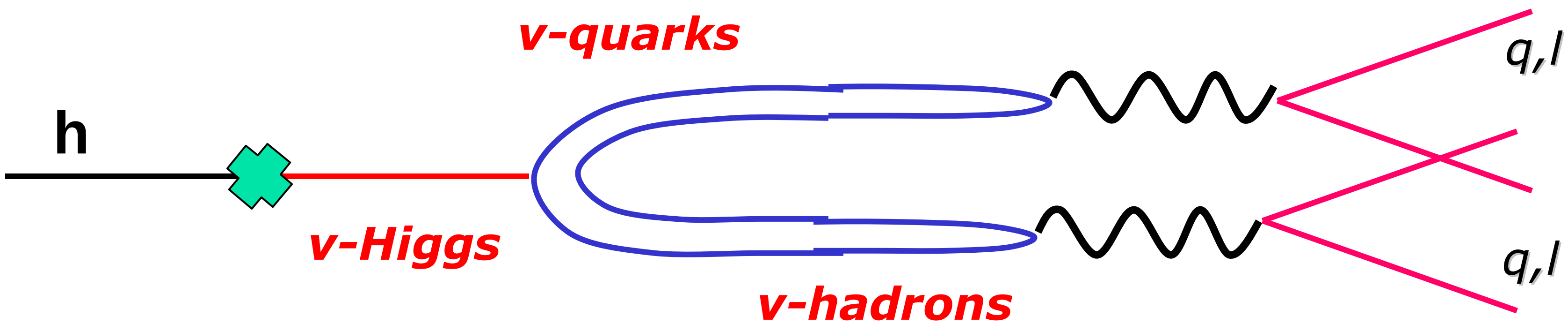
- Some limited searches as a result:

$b' \to Z^0 b$ $\quad Z^0 \to e^+e^-$ CDF collaboration, hep-ex/9805017

$\tilde{N} \to Z^0 + \tilde{G}$ $\quad \to \mu^+\mu^-$ 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



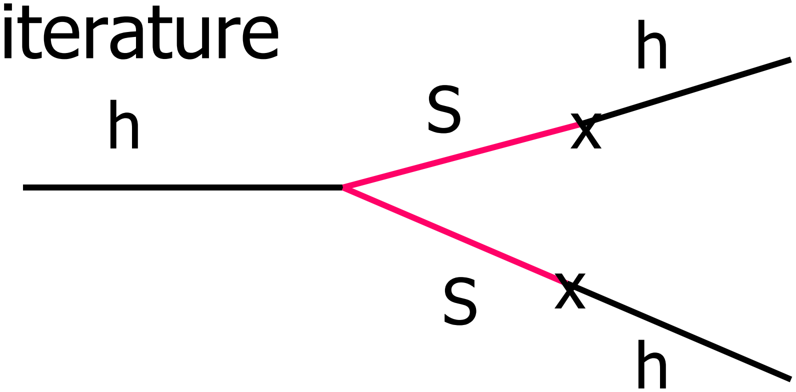
Mixing is not necessarily small → branching is not necessarily small

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



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

Break S → -S symmetry

$$\Gamma_S \propto c \Rightarrow \text{ can be long lifetimes}$$

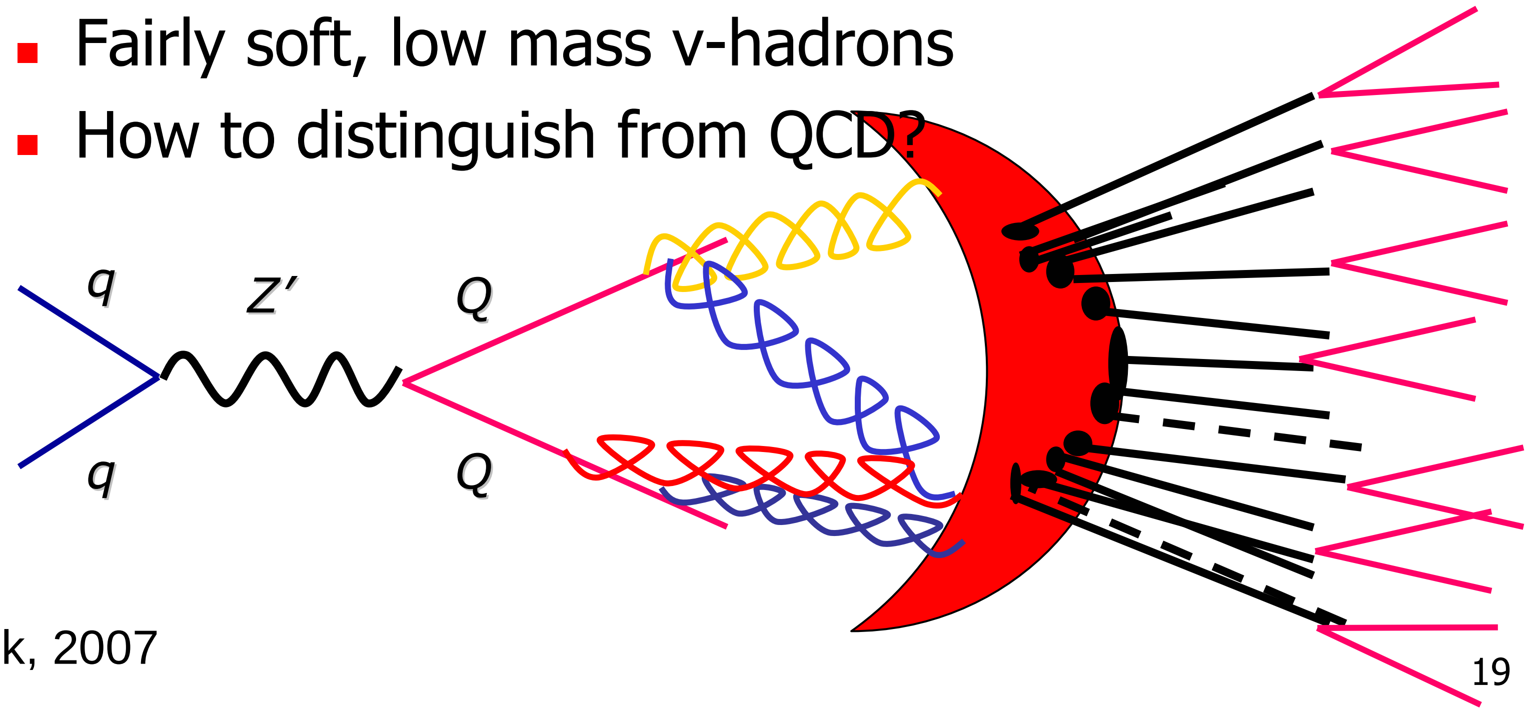
Dermisek and Gunion;
Chang, Fox, Weiner

But if no displaced vertex?

$$\Gamma_{\eta_v \to b\bar{b}} \sim 6\times10^{9}\ \mathrm{s}^{-1} \frac{f_{\eta_v}^2 m_{\eta_v}^5}{(20\ \mathrm{GeV})^7}\left(\frac{10\ \mathrm{TeV}}{\mathrm{m}_{Z'}/g'}\right)^4$$

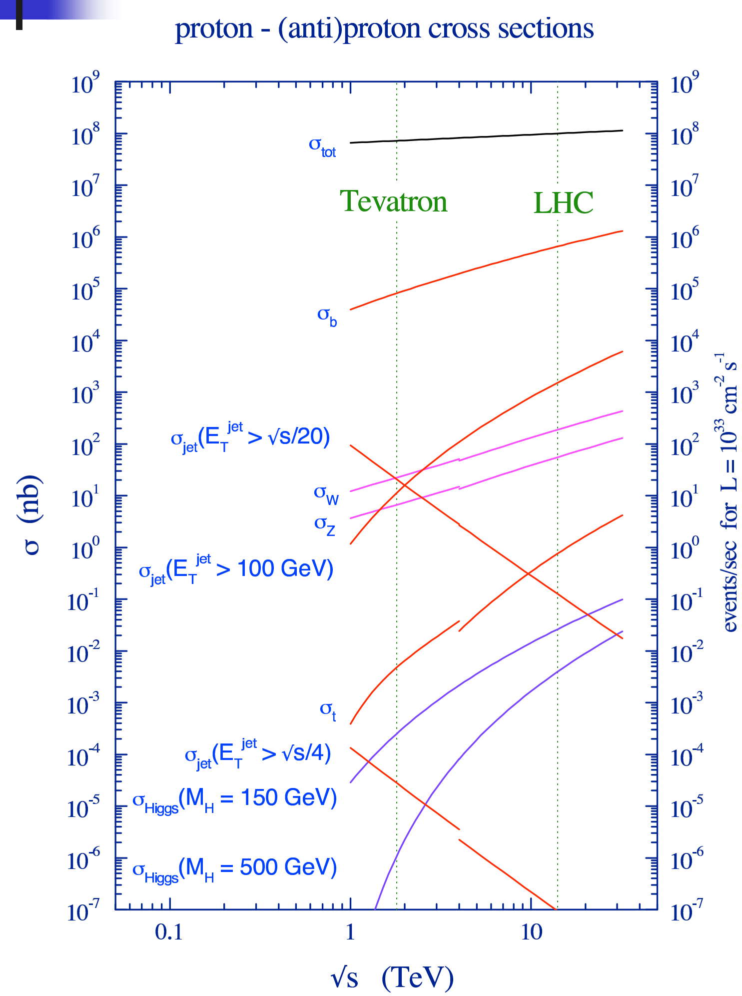
$$\Gamma_{\rho_v \to l\bar{l}} \sim 4\times10^{18}\ \mathrm{s}^{-1} \frac{m_{\rho_v}^5}{(20\ \mathrm{GeV})^5}\left(\frac{10\ \mathrm{TeV}}{\mathrm{m}_{Z'}/g'}\right)^4$$

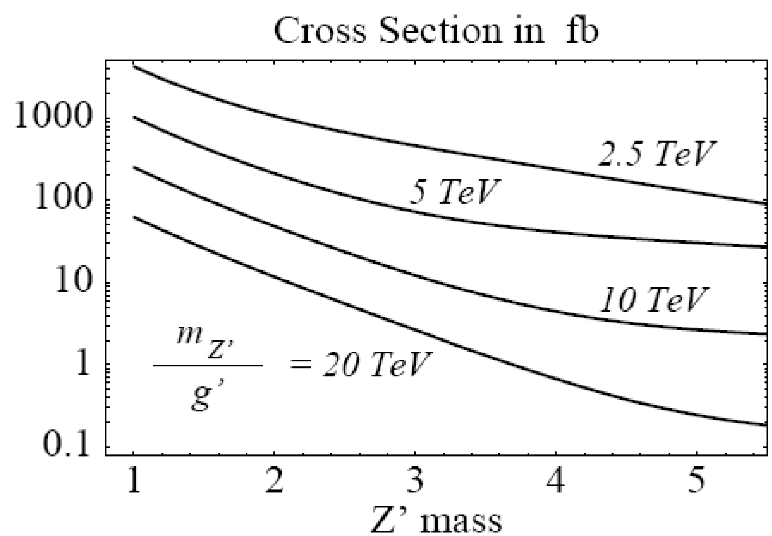
- Challenges:
  - High multiplicities
    - (Lots of stuff in the event)
  - Fairly soft, low mass v-hadrons
  - How to distinguish from QCD?



Han, Si, Zurek, 2007

Backgrounds can be daunting





Use typical energy scales

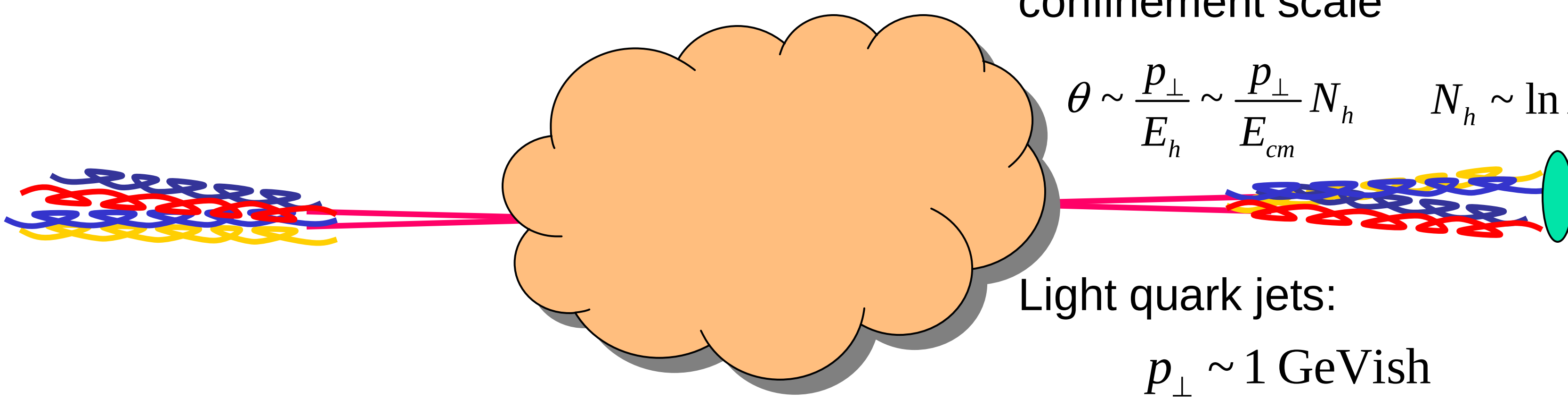
- Low mass v-hadrons
  - Use displaced vertex

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

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

Cone size set by
confinement scale

$$\theta \sim \frac{p_\perp}{E_h} \sim \frac{p_\perp}{E_{cm}} N_h \qquad N_h \sim \ln E_{cm}/m_h$$

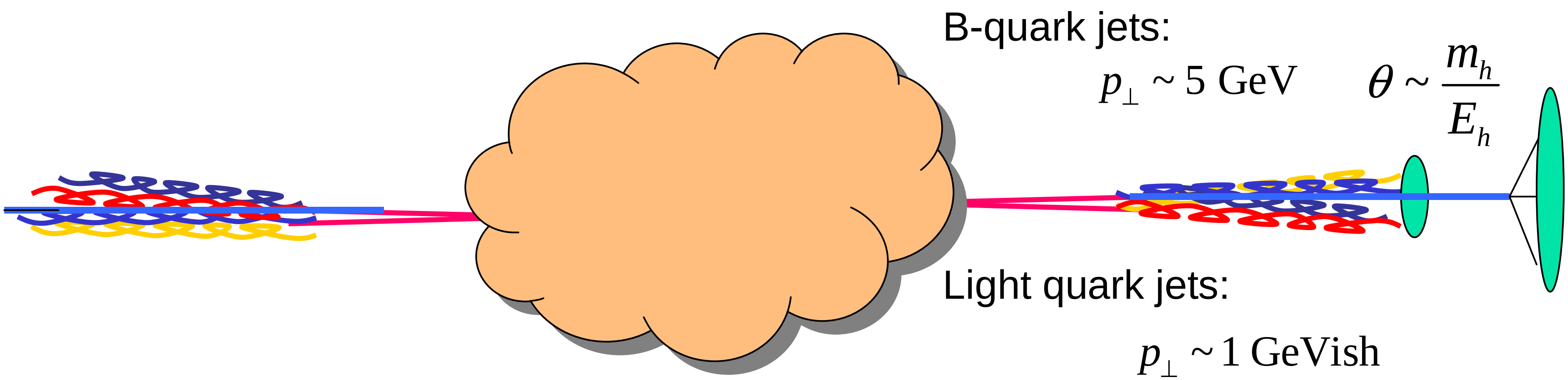


Light quark jets:

$$p_\perp \sim 1\ \mathrm{GeVish}$$

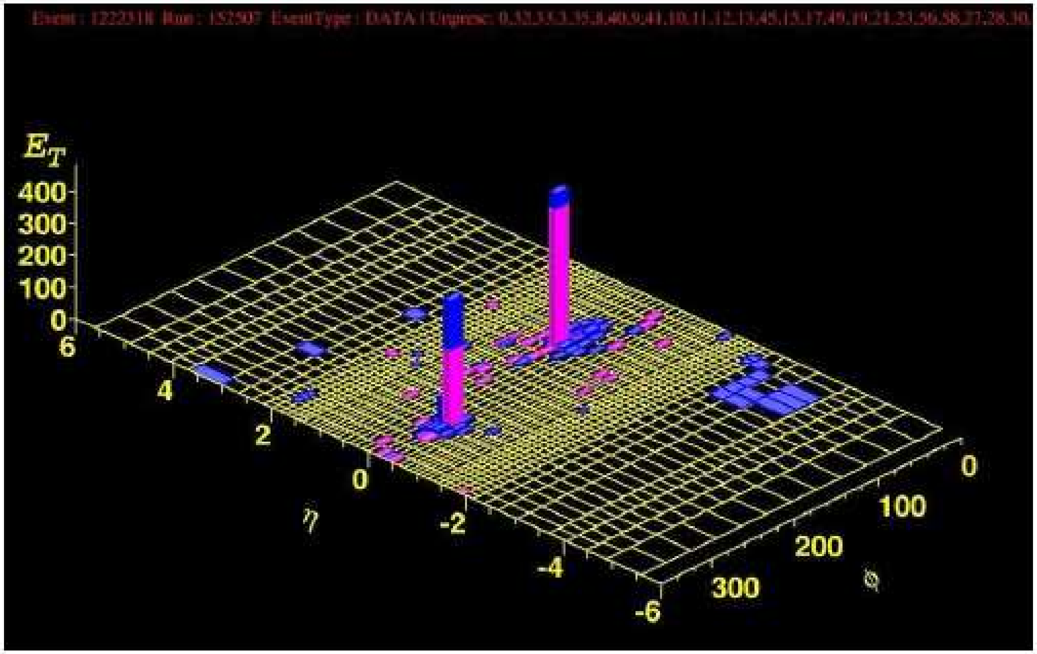
Used in b-tagging

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

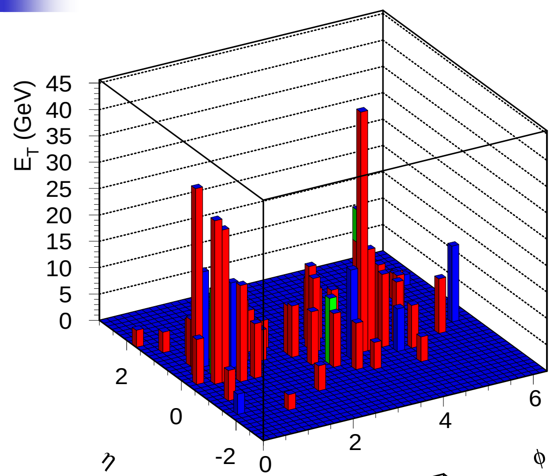


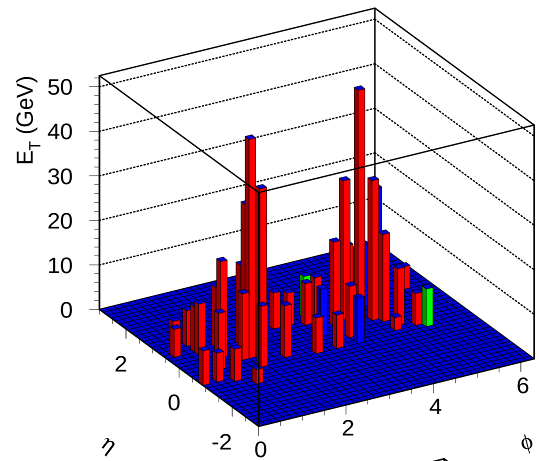
  - Two effects contribute:
    - Parent v-hadrons more widely separated
    - Decay products more widely separated

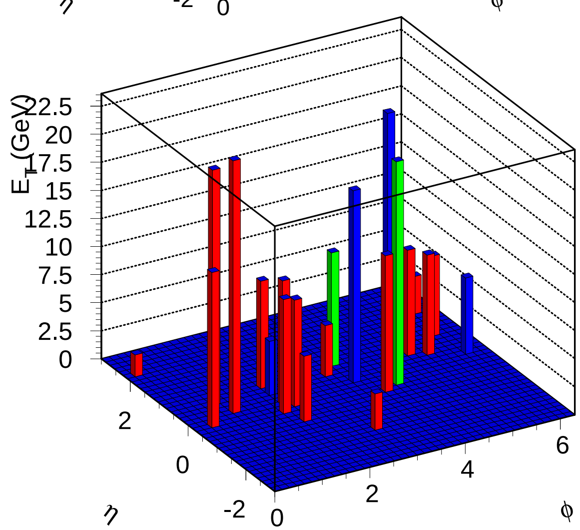
Lego Plot View

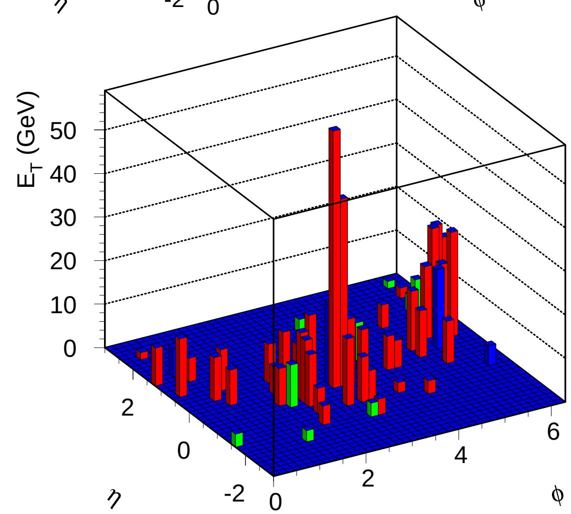


Contrast Hidden Valley Events

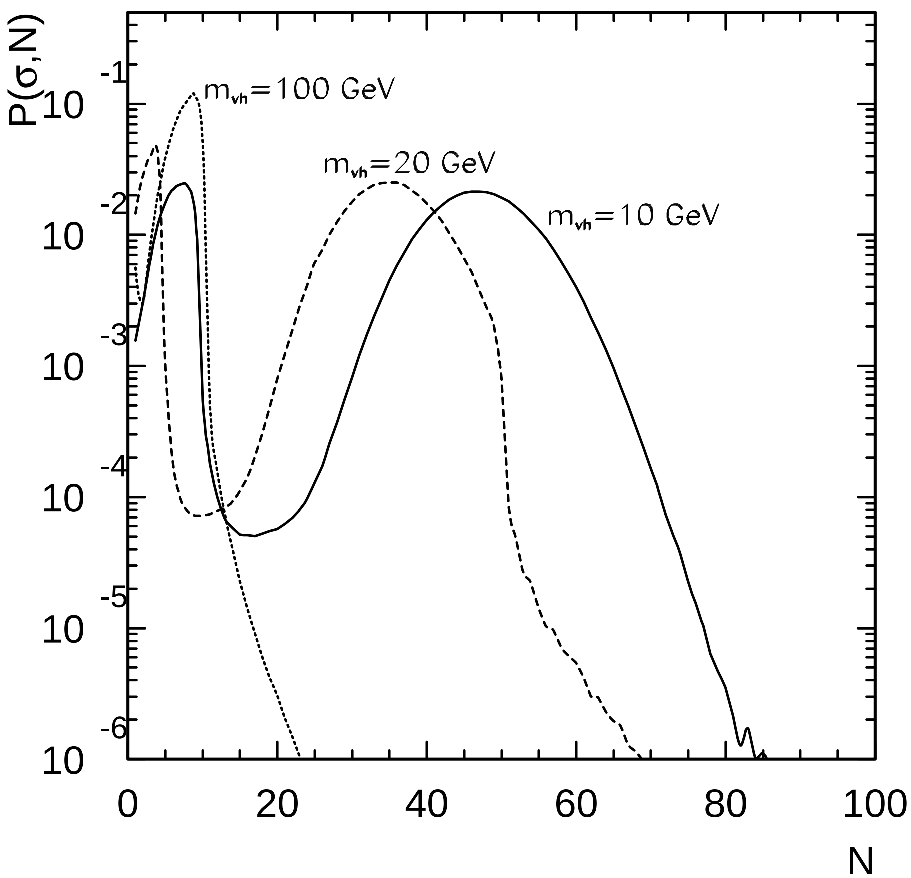








Characterized by high multiplicities

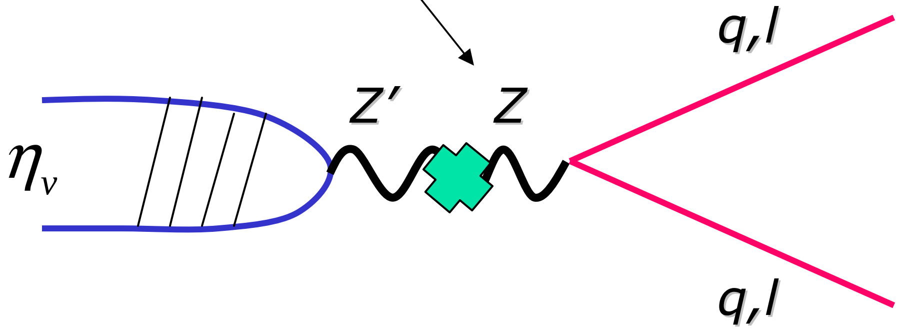


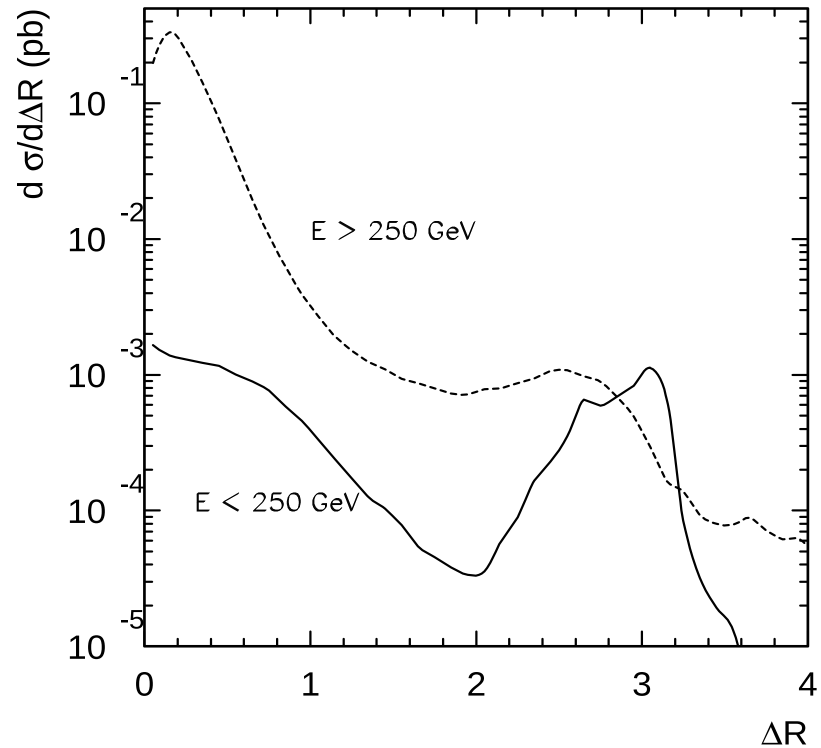
Han, Si, Zurek, 2007

How to quantify these qualitative features?

- Well separated leptons

Strongest constraints derived from Z-Z' mixing at LEP



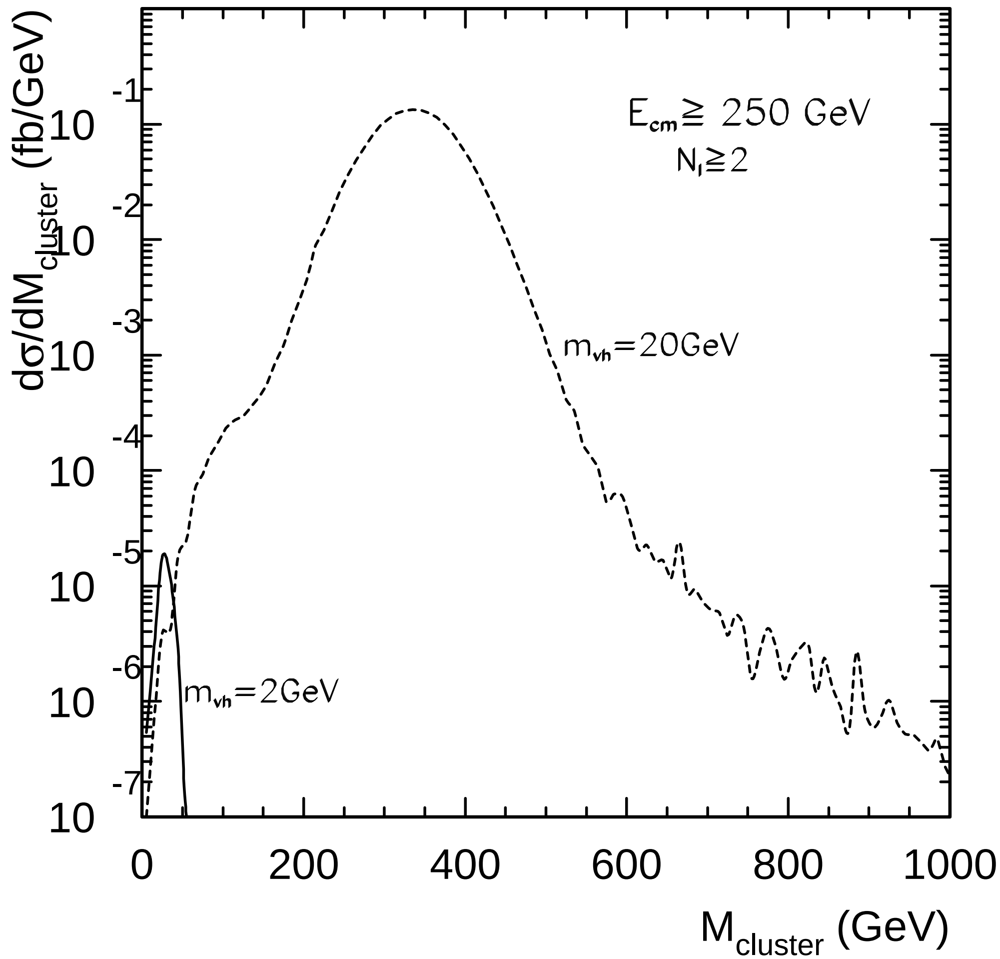


$$\Delta R = \sqrt{\left(\Delta\phi\right)^2 + \left(\Delta\eta\right)^2}$$

Han, Si, Zurek, 2007

Best measure: invariant mass of cluster

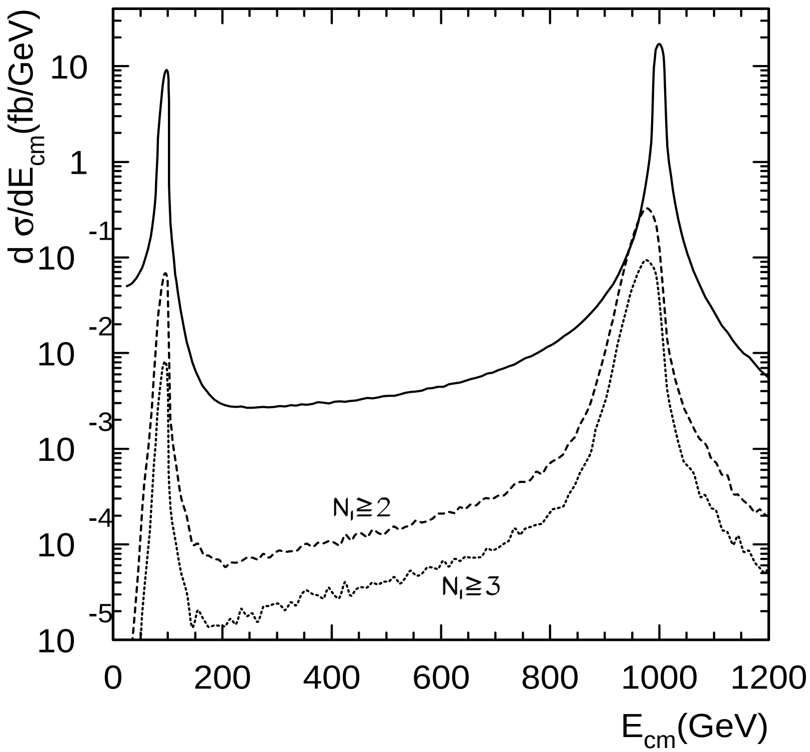
$$m_{clus}^2 = \left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2$$



Highly collinear → low invariant mass

Han, Si, Zurek, 2007

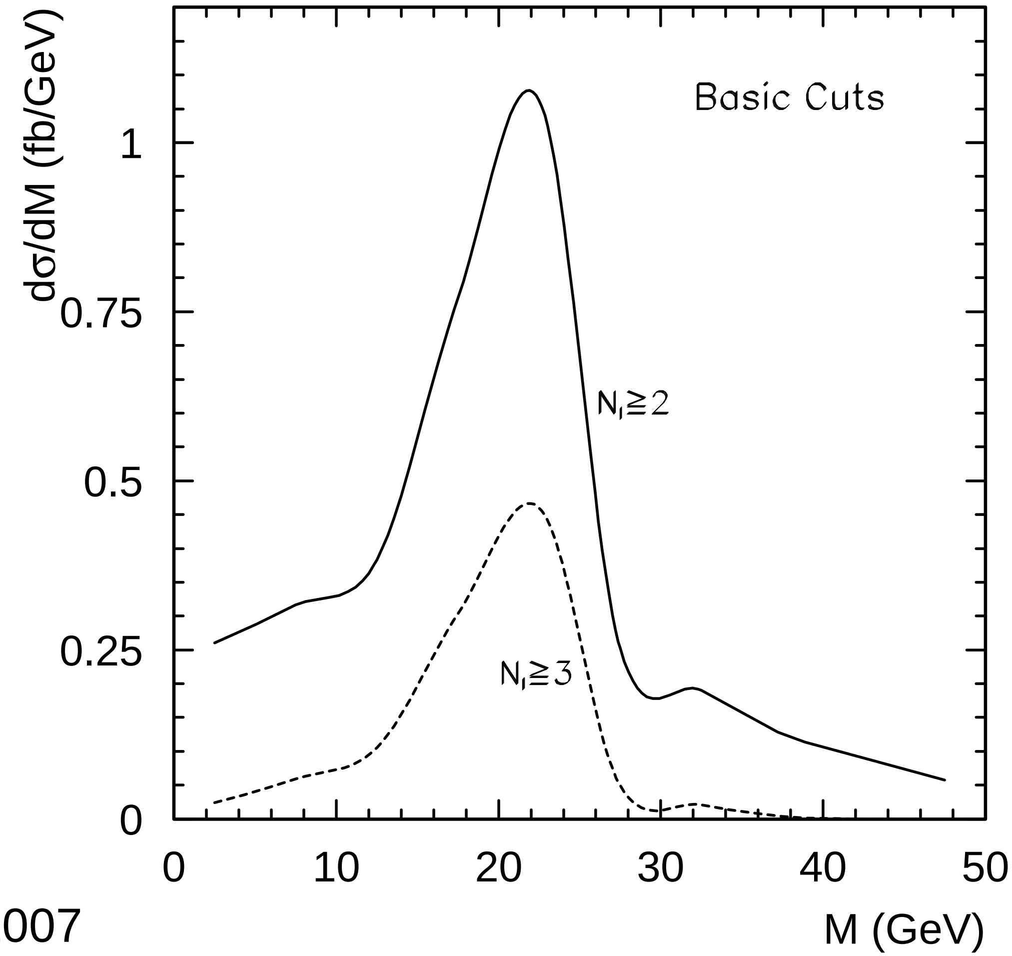
Implement cuts; reconstruct resonance



Han, Si, Zurek, 2007

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

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?

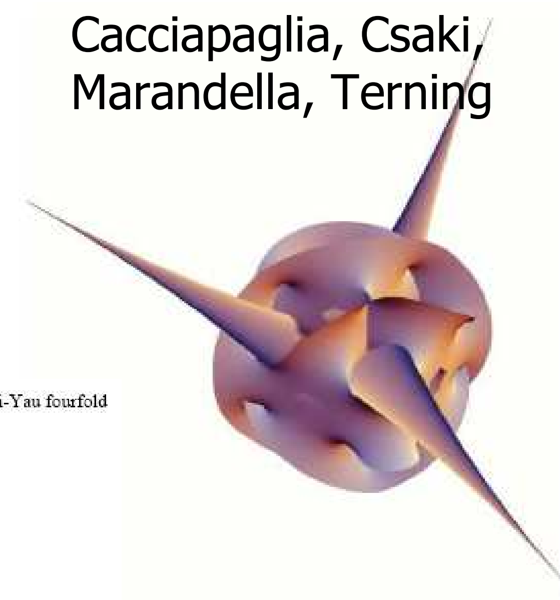
Top-down

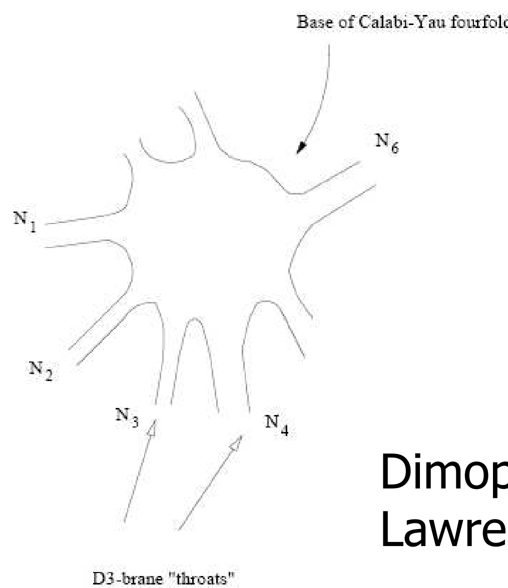
- Well-motivated in bottom-up model-building
  - Gauge mediation, gravity mediation, twin Higgs, hidden Higgs decays…..
- Well-motivated in top-down string constructions
  - Lots of extra matter in string theories
  - What generic way can we get a TeV mass mediator?

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

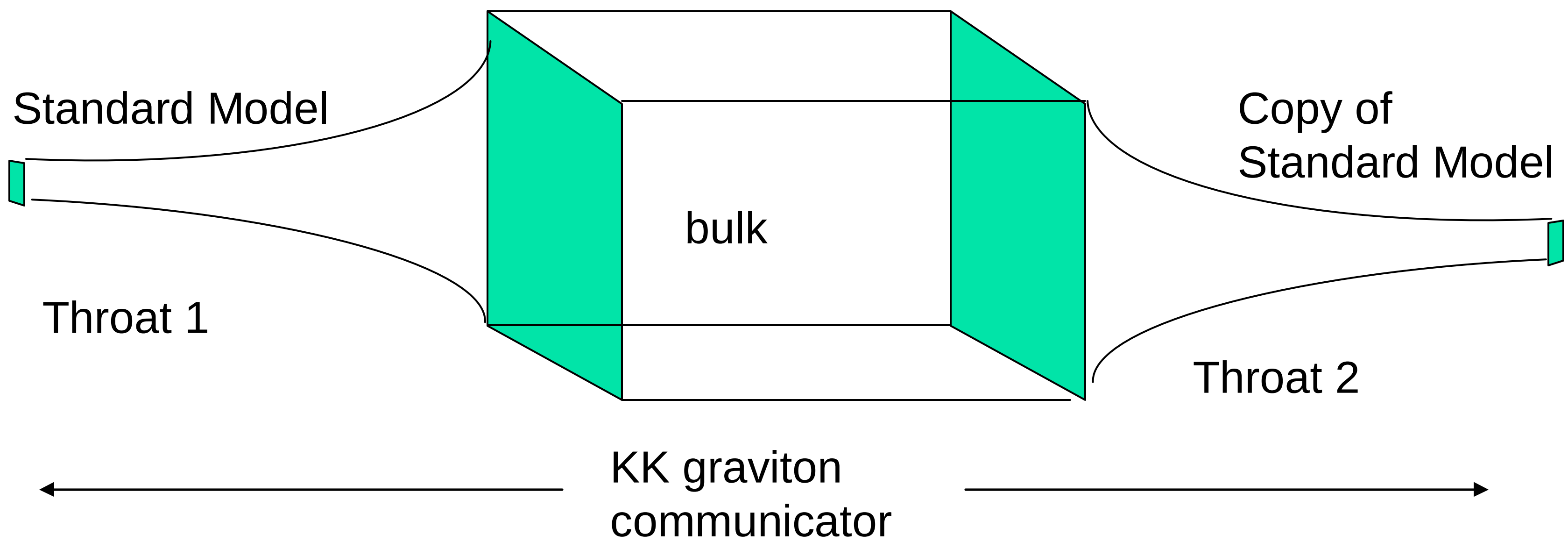
Cacciapaglia, Csaki, Marandella, Terning



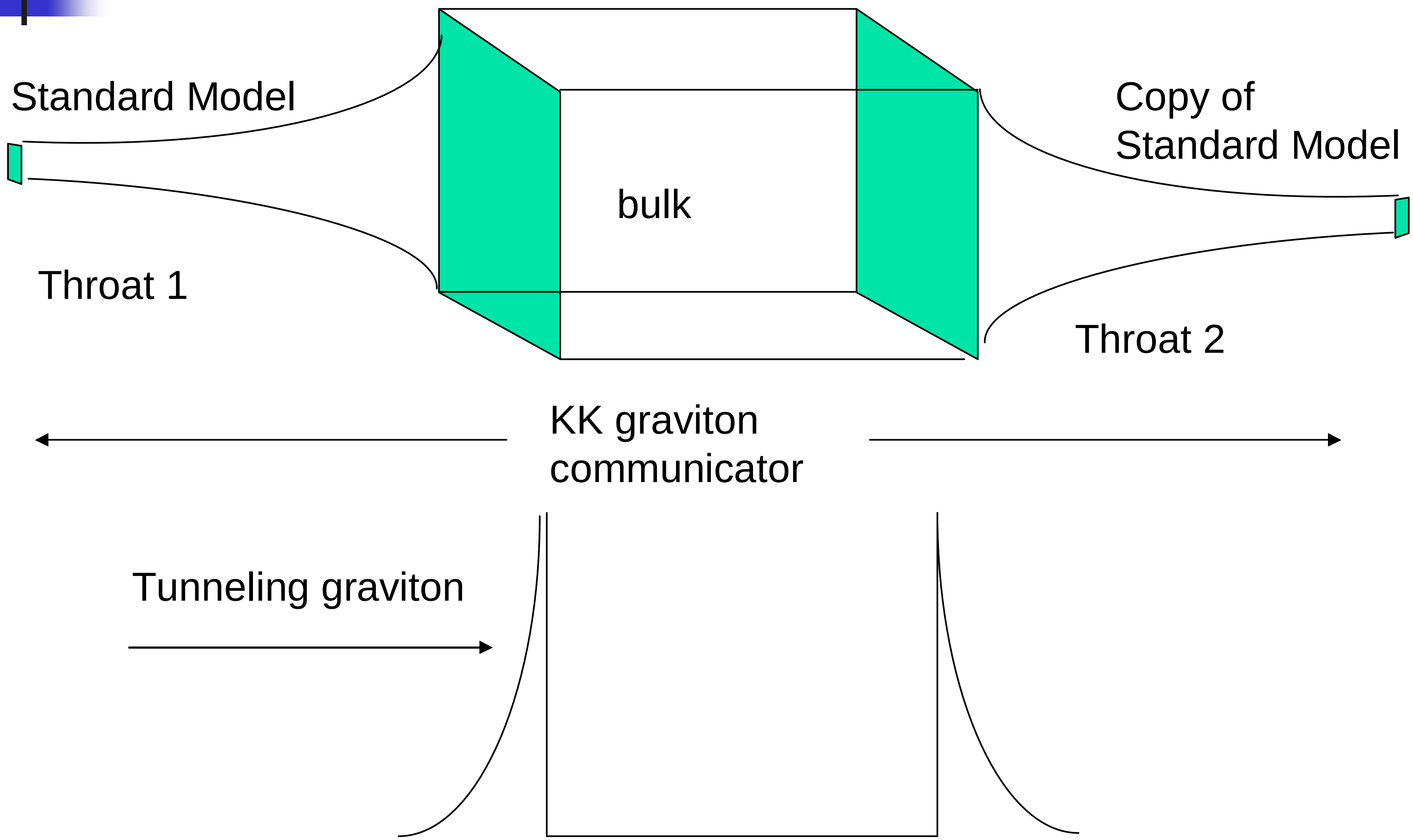


Dimopoulos, Kachru, Kaloper, Lawrence, Silverstein

Two-throat hidden valley model



Two-throat hidden valley model



Two-throat to multi-throat

Resonance condition must be met to obtain significant tunneling

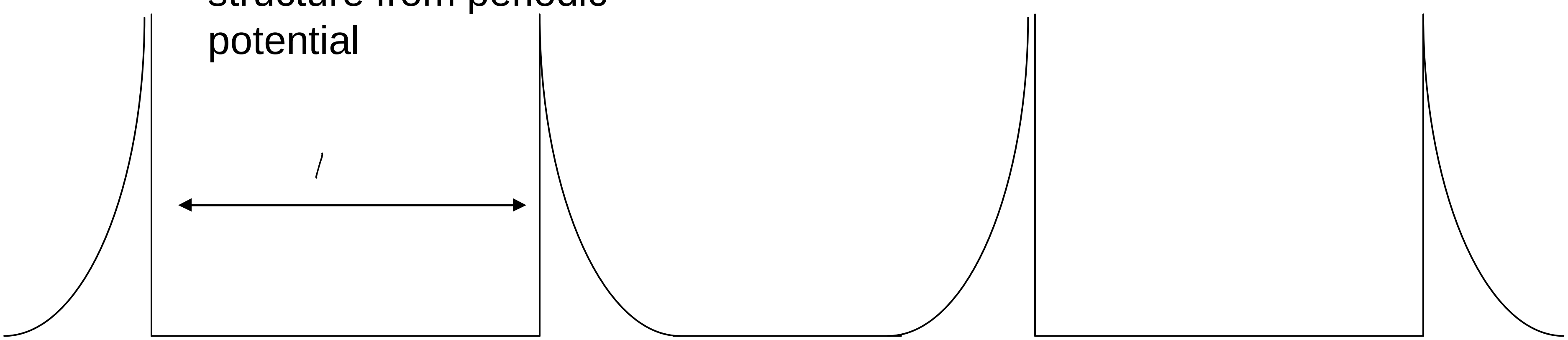
$$P = \left(\frac{\left(t + \frac{1}{t}\right)\left(H_2^- H_1^+ - H_1^- H_2^+\right)}{H_2^{+2} + H_1^{+2} + \left(t - \frac{1}{t}\right) H_2^+ H_1^+} \right)^2$$

$$t = \tan ml$$

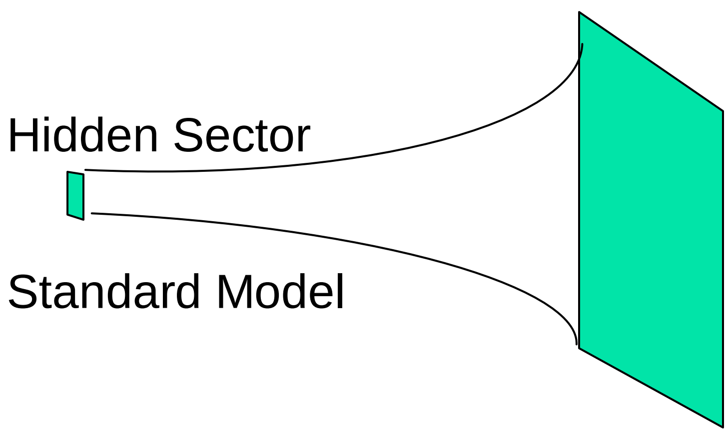
$$t - \frac{1}{t} \ll 1 \Rightarrow m \sim l$$

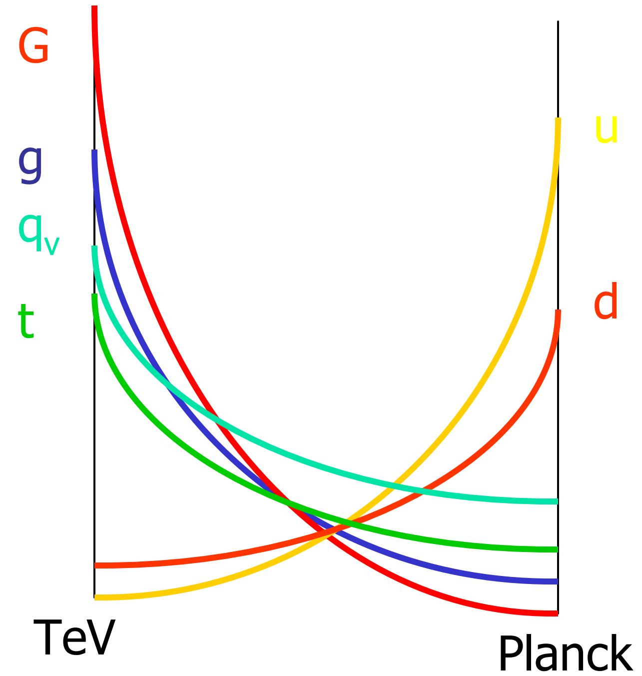
Can obtain band resonance structure from periodic potential

Langfelder, 2006



Or a single throat…





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

Conclusions

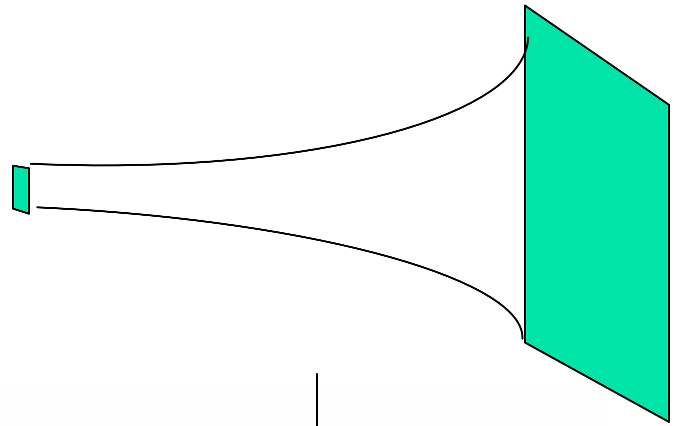
- Considered class of hidden sector models with confining gauge group
  - May search with displaced vertices
  - But events also have unique topology
    - Use
      - Isolated leptons
      - Invariant mass of cluster
  - Classes of models
    - Bottom up
      - Z', Higgs mediators, Mirror sectors
    - 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

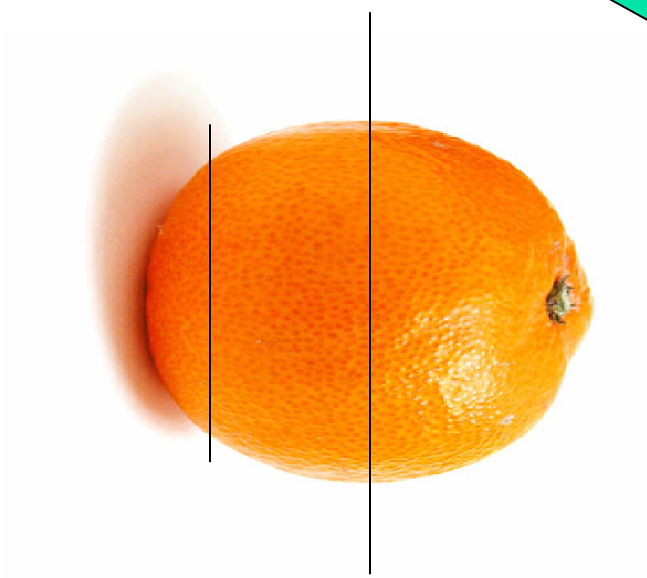
$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$



Metric is sick at large y

Raman Sundrum's
orange slicing analogy:

Truncate space at y = πr_c



In the language of warped throats

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

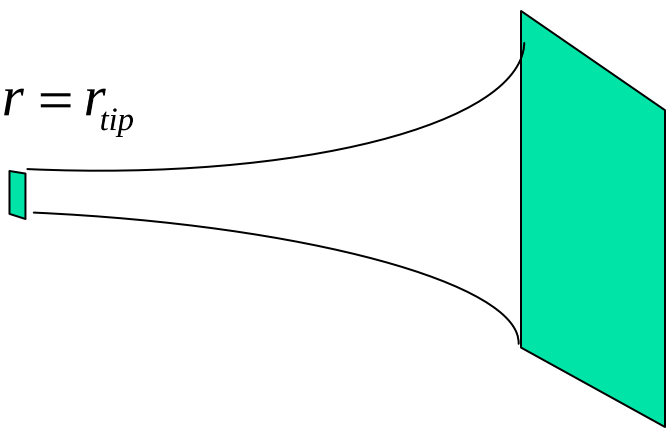
$$ds^2 = f(r)^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + f(r)^{1/2}(dr^2 + r^2 d\Omega^2)$$

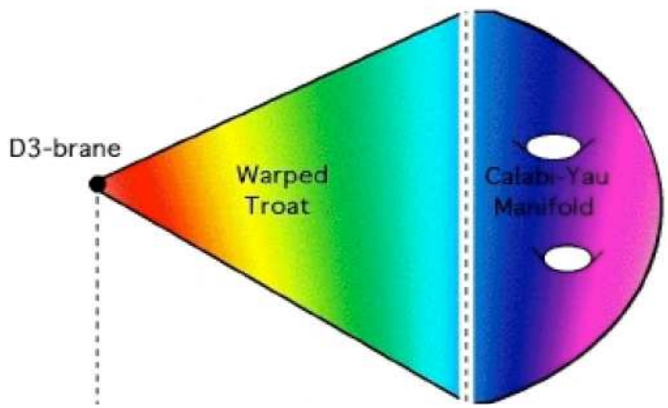
$$\text{AdS: } f(r) = \frac{R^4}{r^4}$$

Divergent r→0
Truncate space at r_{tip}

$$r = e^{-ky}$$

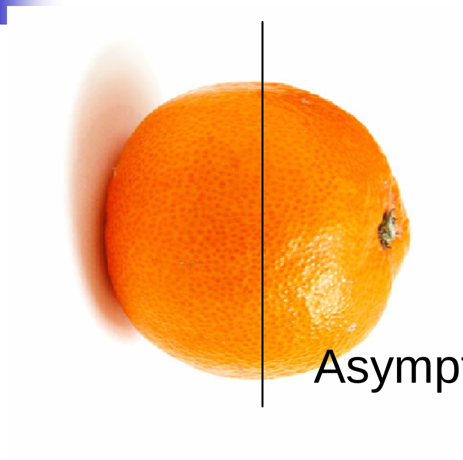
$$r = r_{tip}$$





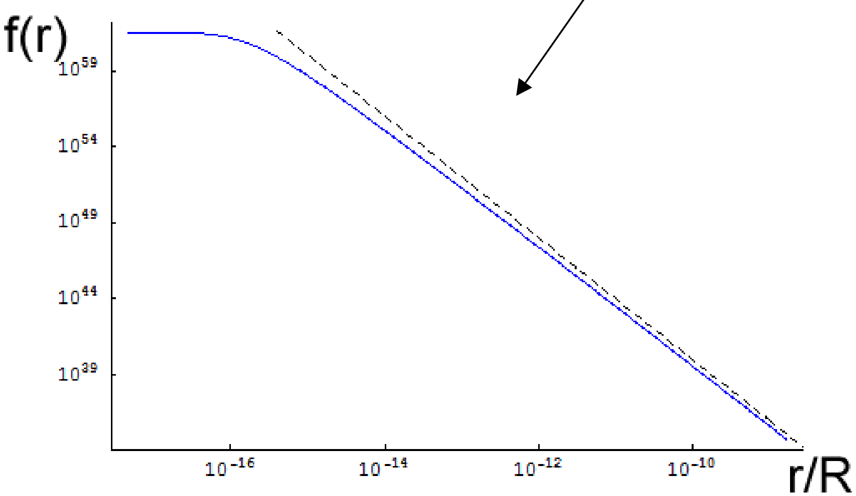
Metrics arising in string theories (from stabilizing moduli with fluxes) often have smooth IR cutoff

Sample string theory metric



Warped deformed conifold or Klebanov-Strassler throat

Asymptotically AdS



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

$$ds_6^2 = \frac{1}{2}\varepsilon^{4/3} K(\tau) \left[\frac{1}{3K^3(\tau)} (d\tau^2 + (g^5)^2) + \cosh^2\left(\frac{\tau}{2}\right) [(g^3)^2 + (g^4)^2] \right.$$
$$\left. + \sinh^2\left(\frac{\tau}{2}\right) [(g^1)^2 + (g^2)^2] \right],$$

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

$$h(\tau) = \alpha \frac{2^{2/3}}{4} I(\tau) = (g_s M\alpha')^2 2^{2/3} \varepsilon^{-8/3} I(\tau),$$

$$I(\tau) \equiv \int_\tau^\infty dx \frac{x\coth x - 1}{\sinh^2 x} (\sinh(2x) - 2x)^{1/3}.$$

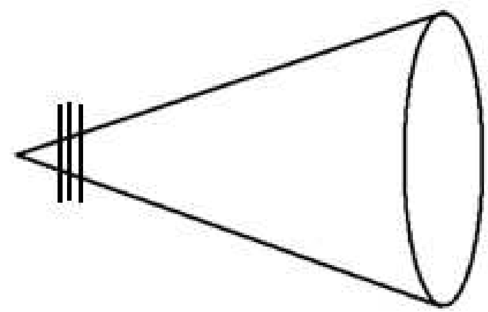
Warped deformed conifold

Singular conifold

$$ds_6^2 = dr^2 + r^2 ds_{T^{1,1}}^2$$

Stack of D3-branes at tip

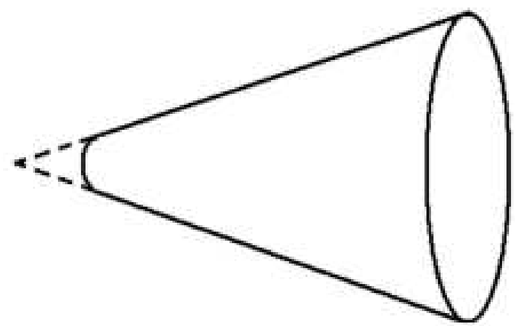
$$AdS_5 \times T^{1,1}$$



Klebanov-Witten

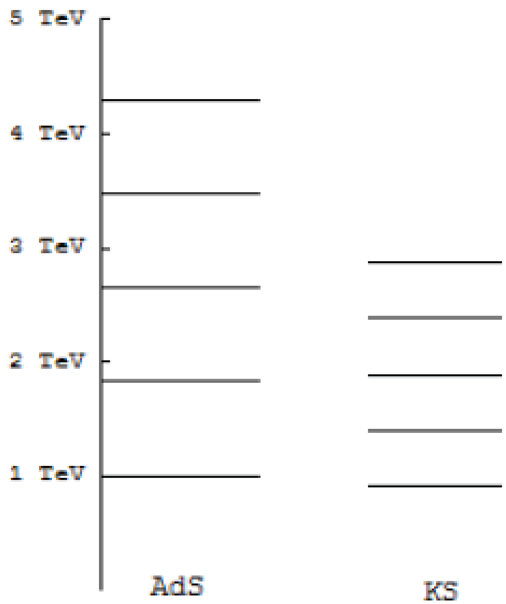
NS-NS and RR fluxes on cycles

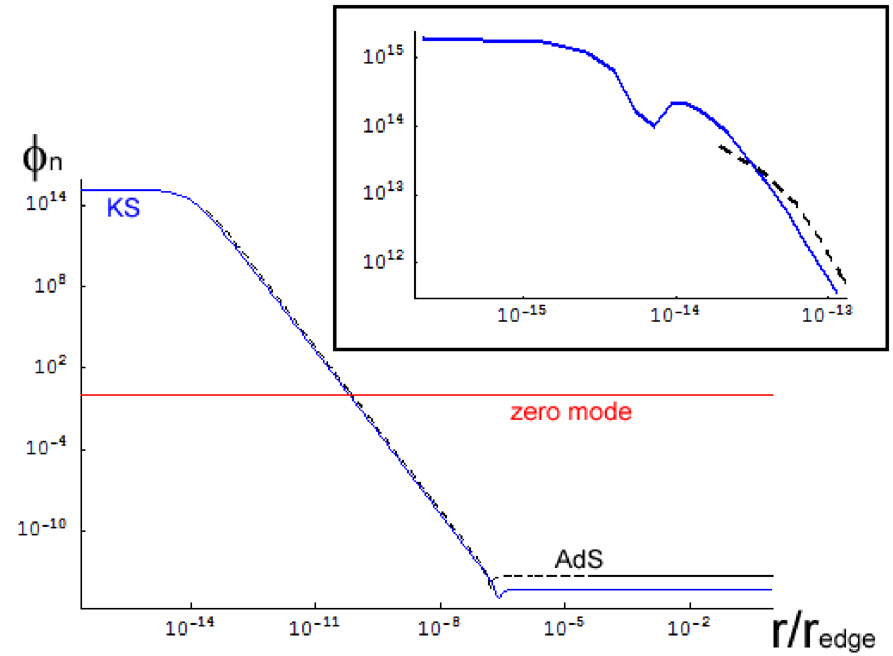
Warped deformed conifold



Klebanov-Strassler

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

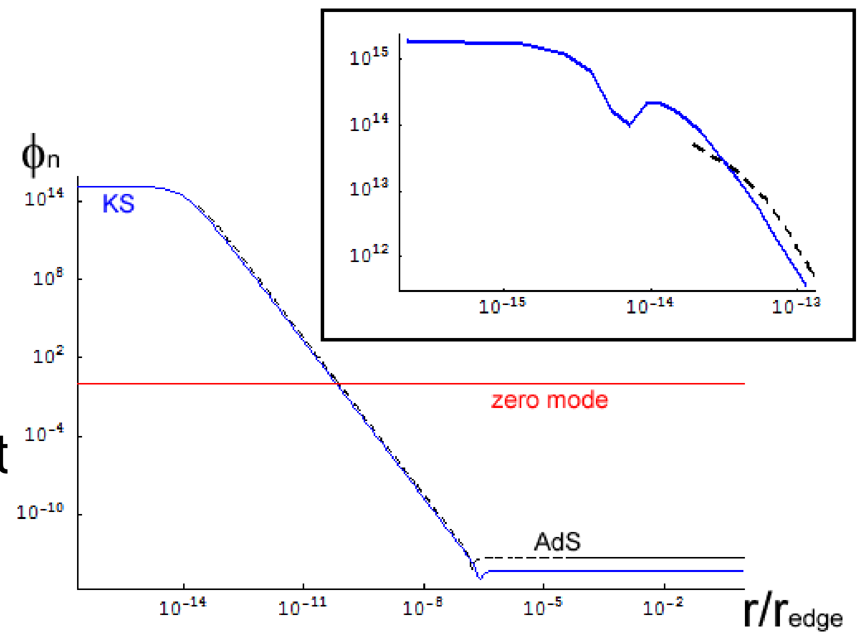
$$V_w \delta_{m,n} = \int d^{D-4} y \sqrt{\tilde{g}}\, f^{(D-6)/4}(y) \phi_n(y) \phi_m(y)$$

- Oscillation to minimum just volume factor is peaking

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

$$L = \frac{1}{\overline{M}_{pl}} h^0_{\mu\nu} T^{\mu\nu} + \frac{1}{\Lambda_{KK}} \sum h^n_{\mu\nu} T^{\mu\nu}$$

$$\Lambda_{KK} = \overline{M}_{pl} / \phi_n(r_{IR})$$

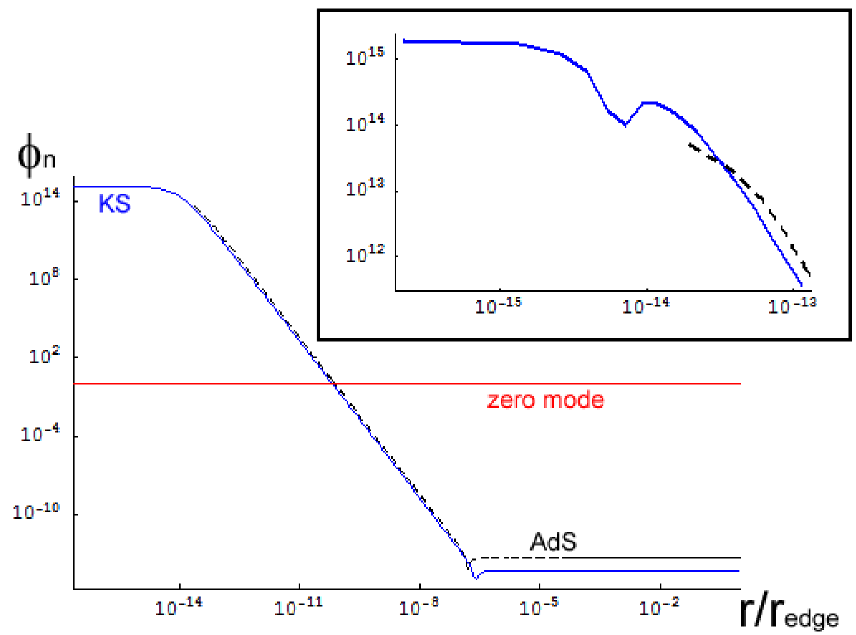


Mode dependent couplings

$$L = \frac{1}{\overline{M}_{pl}} h^0_{\mu\nu} T^{\mu\nu} + \frac{1}{\Lambda_{KK}} \sum h^n_{\mu\nu} T^{\mu\nu}$$

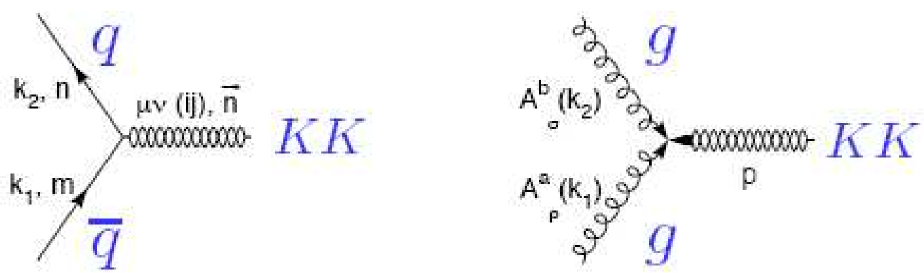
$$\Lambda_{KK} = \overline{M}_{pl} / \phi_n(r_{IR})$$

KK Mode	RS Mass	KS Mass	RS Coupling	KS Coupling
1	1.000	1.000	51.15	1.975
2	1.831	1.506	51.15	1.244
3	2.655	2.012	51.15	0.921
4	3.477	2.519	51.15	0.737
5	4.298	3.027	51.15	0.619

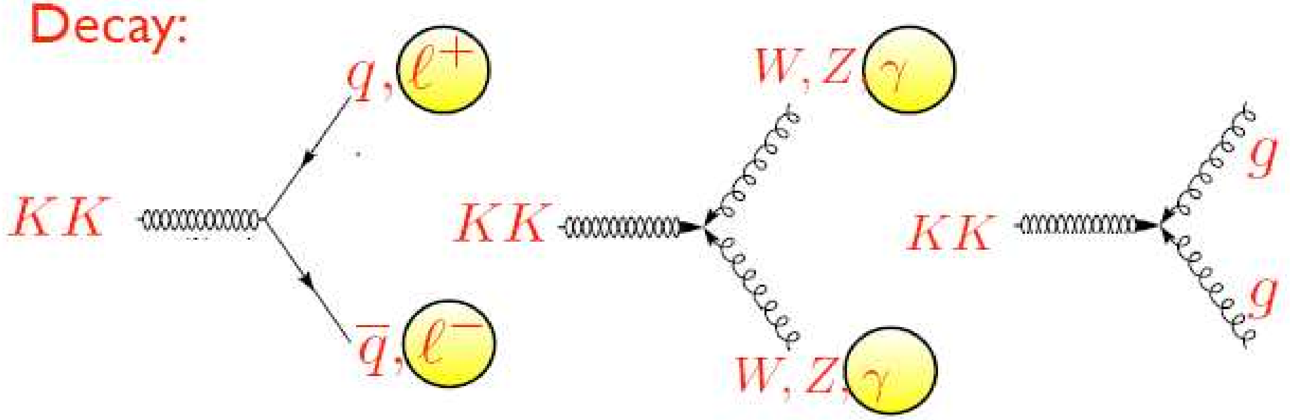


Implications for phenomenology

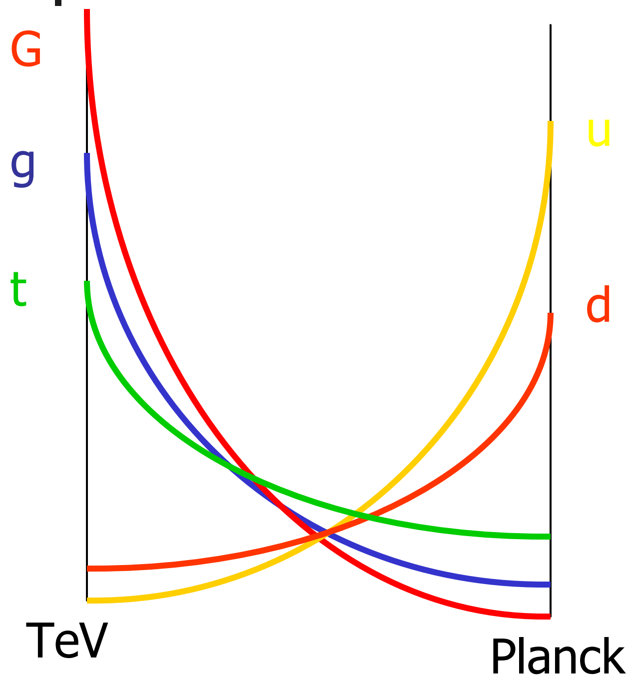
Production:



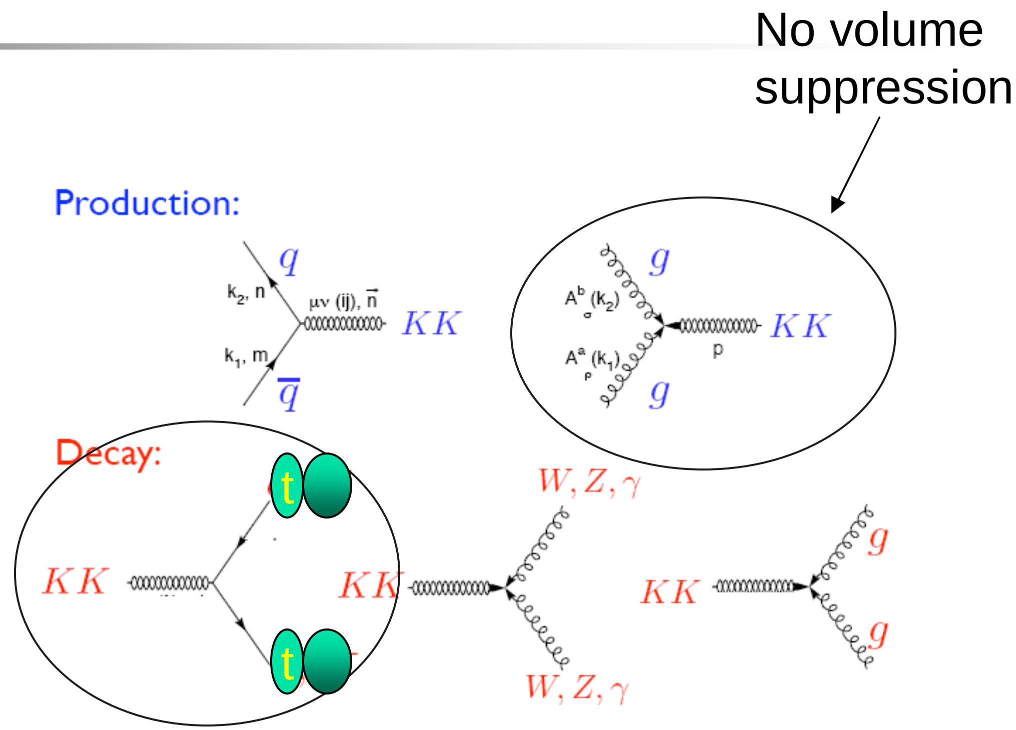
Decay:



Dominant Production and Decay Depends on Localization



Solve flavor problem



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

Observations

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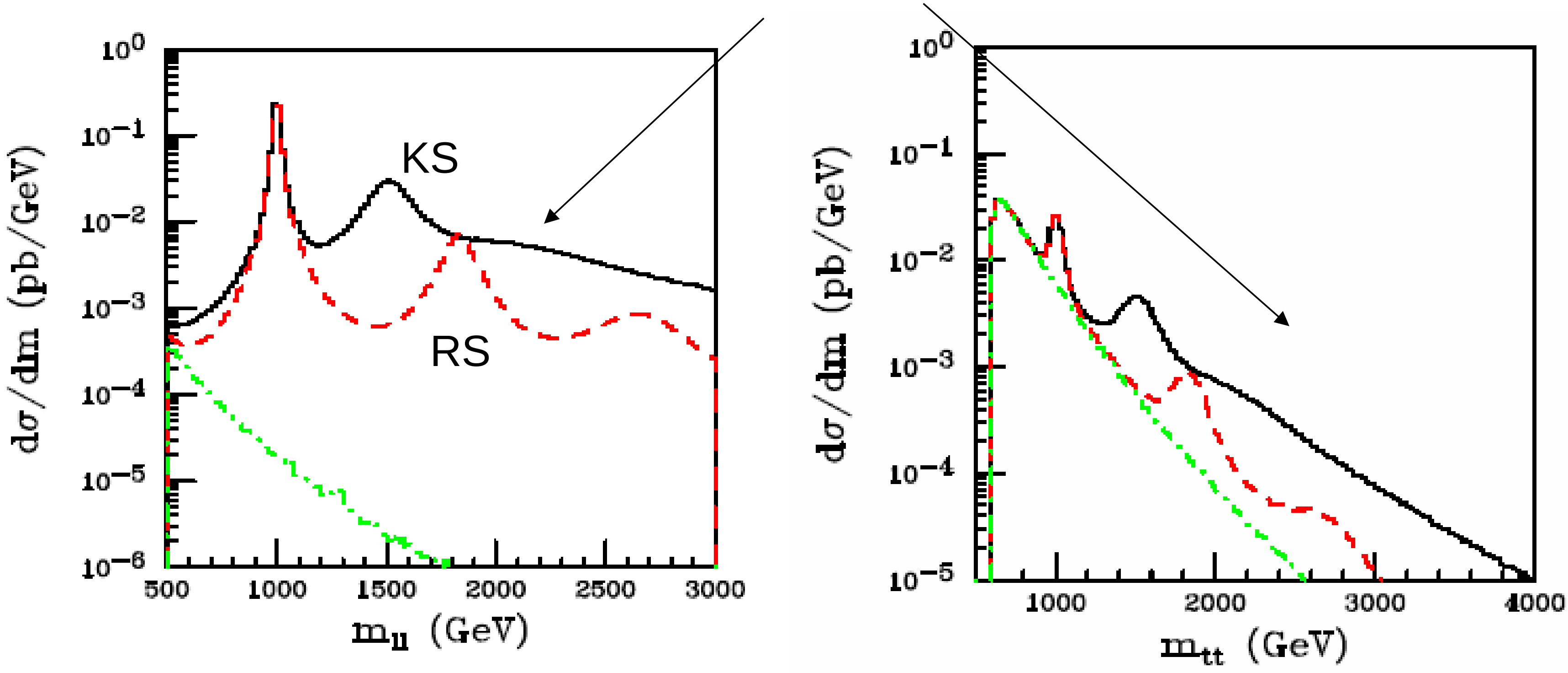
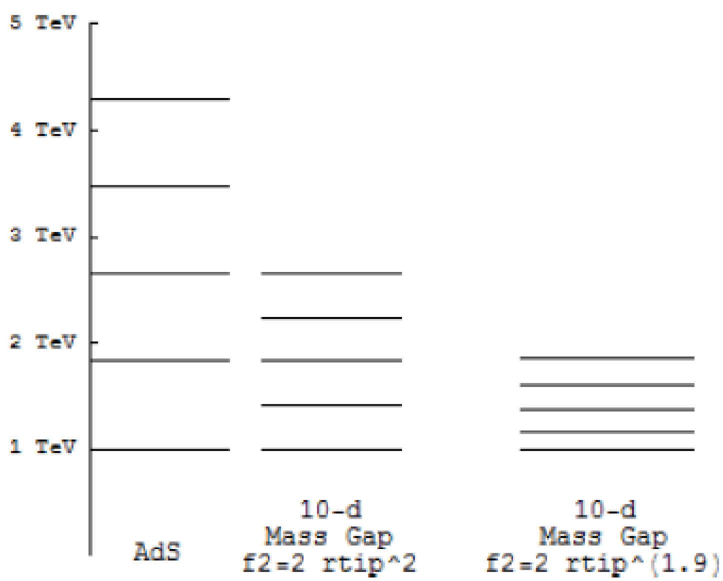
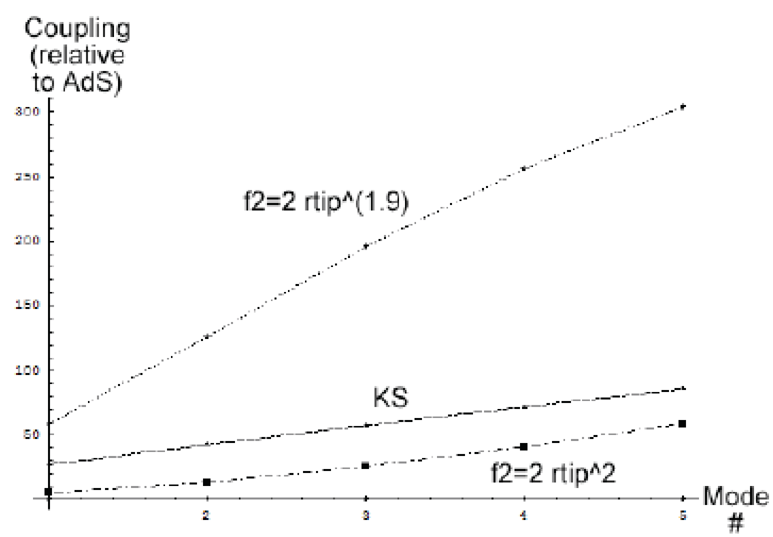
Narrower spacing and broader peaks at higher KK mode



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