Theory Perspective of Top Production:

Top Resonances

Tim M.P. Tait

NORTHWESTERN UNIVERSITY

Argonne NATIONAL LABORATORY

Aspen Winter
February 10 2009

Outline

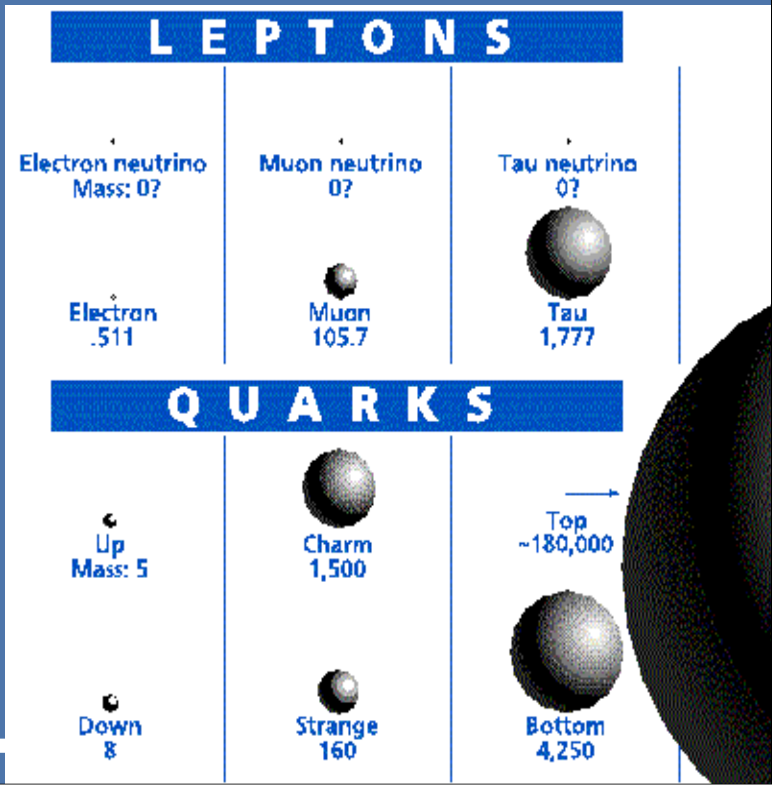
- Top Resonances are EVERYWHERE!
  - Models, Models, and more Models
- High Mass Resonances and Boosted Tops
- Multi-top Signals
- Outlook

Top is a very special Quark!

The huge top mass affects the way we think about top in the context of physics beyond the Standard Model.

Many models predict that top is special in order to explain its mass.

Still others give it a special role as a result of its mass.



Specific Models

- Before talking about the phenomenology of resonances that decay into tops, let's run through some examples of theories that predict such objects.
- These models attempt to solve an impressive array of problems, from explaining the large top mass, to solving the hierarchy problem.

Topcolor

- The topcolor models explain the top mass and EWSB by introducing new dynamics for top.
- A new strong force is broken (in some way) at the scale of a few TeV. The residual low energy effect is a funny interaction for the top:

Hill PLB266, 419 (1991)

$$\frac{g^2}{M^2}\left[\overline{Q}_3 t_R\right]\left[\bar{t}_R Q_3\right] \qquad Q_3 \equiv \begin{bmatrix} t_L \\ b_L \end{bmatrix}$$

- This new interaction causes a scalar bound state to form with the right charges to play the role of the Higgs!

Bardeen, Hill, Lindner, PRD, 1647 (1990)

$$\overline{Q}_3 t_R \Leftrightarrow \Phi!$$

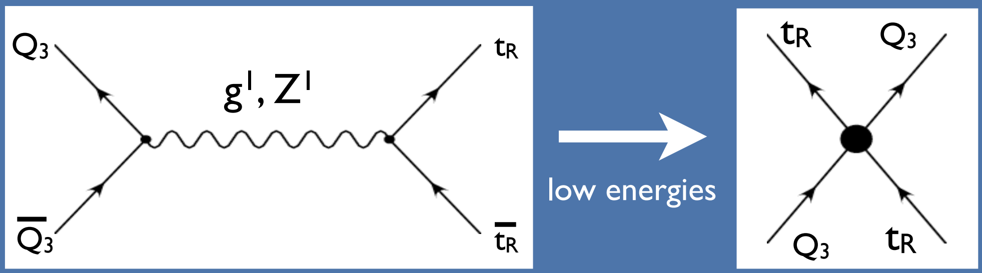
(color singlet, SU(2) doublet, Y=+1)

A Higgs Made from Tops

- Top is heavy because the Higgs “remembers” that it is made out of tops.
  - Or in other words, the top Yukawa coupling is a residual of the strong topcolor force.
- Variations of topcolor can either explain the top mass but not all of EWSB (top-color assisted technicolor) or the top mass and EWSB (top-seesaw).
- A common feature is the need for those four top interactions to form a bound state Higgs.

How Topcolor Works

- The interesting part for this talk is where that funny four top interaction came from.
- Topcolor generates it by the massive exchange of a color octet and a color singlet vector particle.



coupling to top

$$\frac{g^2}{M^2}\left[\overline{Q}_3 t_R\right]\left[\bar{t}_R Q_3\right]$$

Mass of vector

- So we invariably have a ~TeV mass gluon-like object (and often a Z' too) which couples strongly to top!

Topflavor

- Topflavor proposes that there is a separate SU(2) interaction for the third family.
  - This can help explain the top mass in technicolor.

    Chivukula, Simmons, Terning PLB331, 383 (1994)
  - It has also been used to increase the SUSY light Higgs mass by adding D-terms.

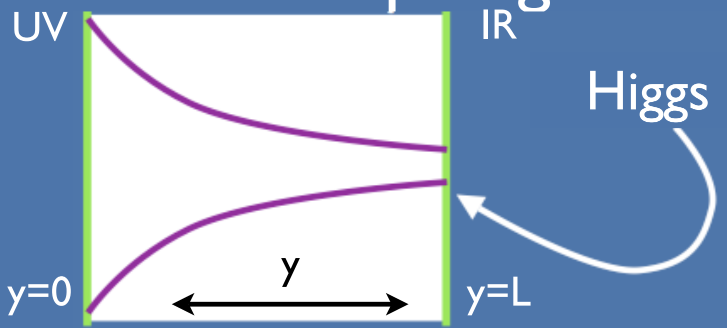
    Batra, Delgado, Kaplan, TT JHEP 0402, 043 (2004)
  - Its first order phase transition can generate the baryon asymmetry of the Universe.

    Shu, TT, Wagner PRD75, 063510 (2007)
- The extra SU(2) group contains a Z' and W's which couple more strongly to the third family.

Randall Sundrum

- Randall Sundrum models propose an extra dimension with a warped geometry:

Randall, Sundrum PRL83, 4690 (1999)

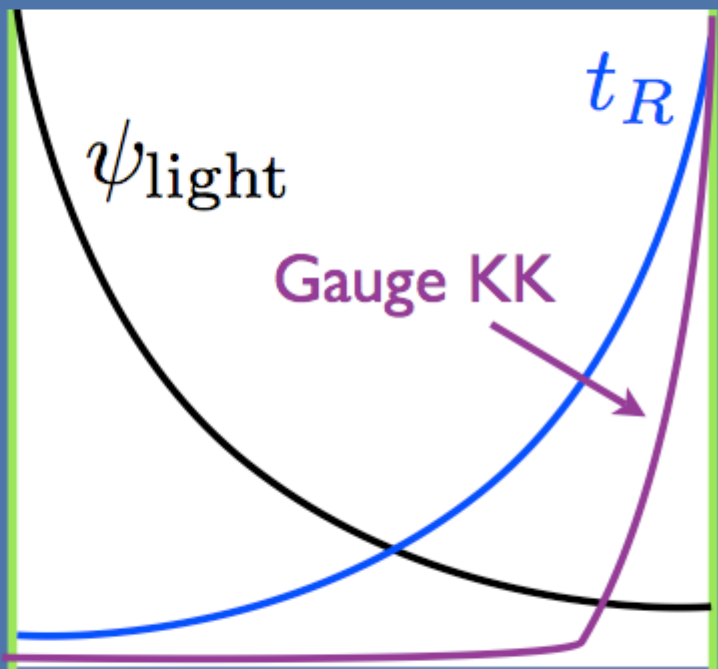


$$ds^2 = e^{-2ky} dx^2 - dy^2$$

$$M(y \sim L) \to M e^{-kL} \sim \text{ TeV}$$

- They solve the hierarchy problem by confining the Higgs to an "IR" brane where the natural scale of physics is TeV.
- The most popular models have the entire Standard Model in the bulk. Thus, every SM particle becomes a "tower" of Kaluza-Klein modes.

Couplings in RS



The warping results in KK modes living close to the IR brane.

- The way particles couple is given by the integral of their profiles in the extra dimension:

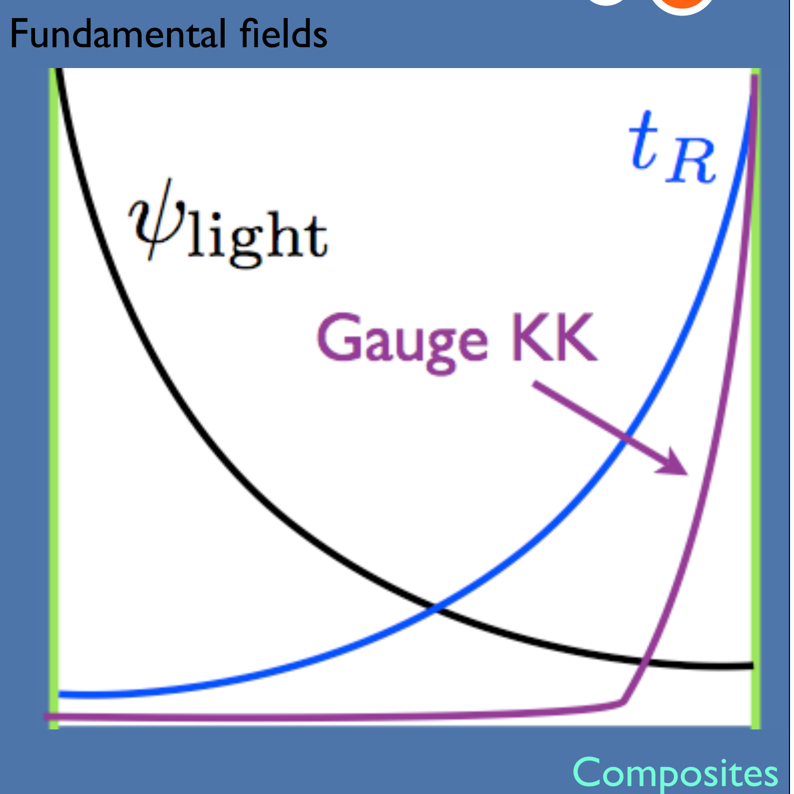
$$g_{ijk} = \int_0^L dy\, f_i(y) f_j(y) f_k(y)$$

- We can arrange the zero modes as we like:
  - Light fermions do best close to the UV brane to minimize precision EW corrections.
  - The top (at least t_R) MUST live close to the IR brane in order to produce the observed top mass.

Top couples more strongly to KK modes!

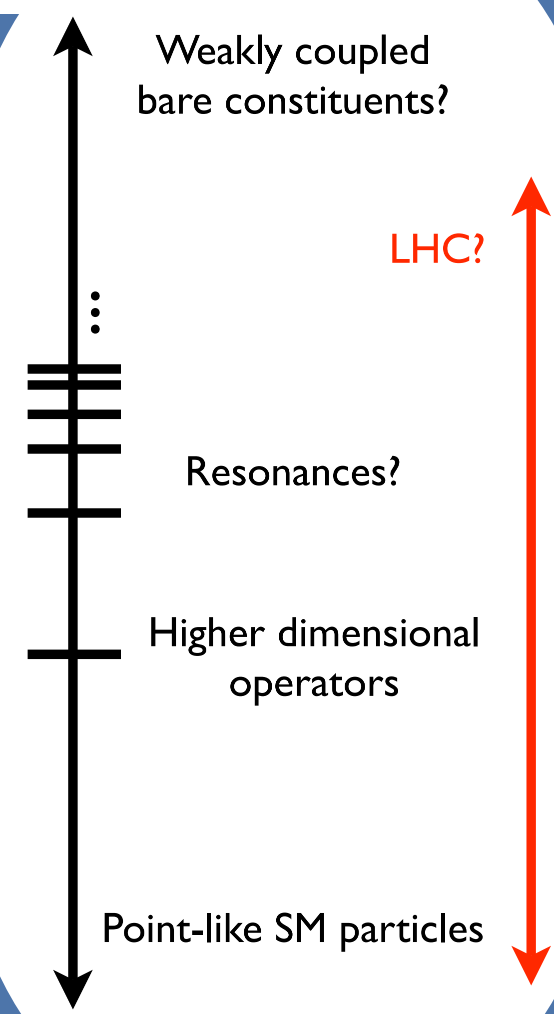
From 5d to Composite

- The AdS/CFT correspondance suggests that RS may actually be a weakly coupled way to describe a certain kind of strongly coupled four dimensional theory.
- In that "dual" interpretation, the IR brane fields (Higgs and top) are composites formed when the strong theory confines.
- In that picture, the top couples strongly to the KK modes because they are also composites. There is a residual of the strong force that bound them.



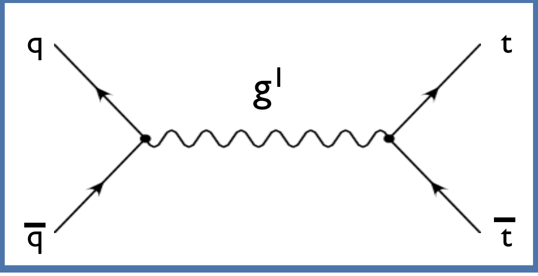
A Composite Top?

- More generally we can ask what kind of phenomena result when the top is a composite, resulting from some constituents bound together by some new force.
  - Since the top is colored, some of its constituents must be too.
  - We can imagine higher resonances (like the rho mesons of QCD). They are probably colored as well.
  - We expect they must couple strongly to top. It may be they couple very very weakly to other quarks.



KK Gluon

- I will focus on color octet vectors which decay into top pairs. The neutral bosons have very similar phenomenology, but usually smaller rates.
- I can use the first KK gluon of Randall-Sundrum as an example:
  - It has large coupling to top and reduced coupling to light quarks.
  - Studies exist for masses from a few hundred GeV to a few TeV.
  - It has another interesting feature - it couples more strongly to the right-handed top than the left-handed top. So we can use it as a laboratory to study polarized tops coming from resonance decay.
- It is produced as an s-channel resonance from a $q\bar{q}$ initial state:



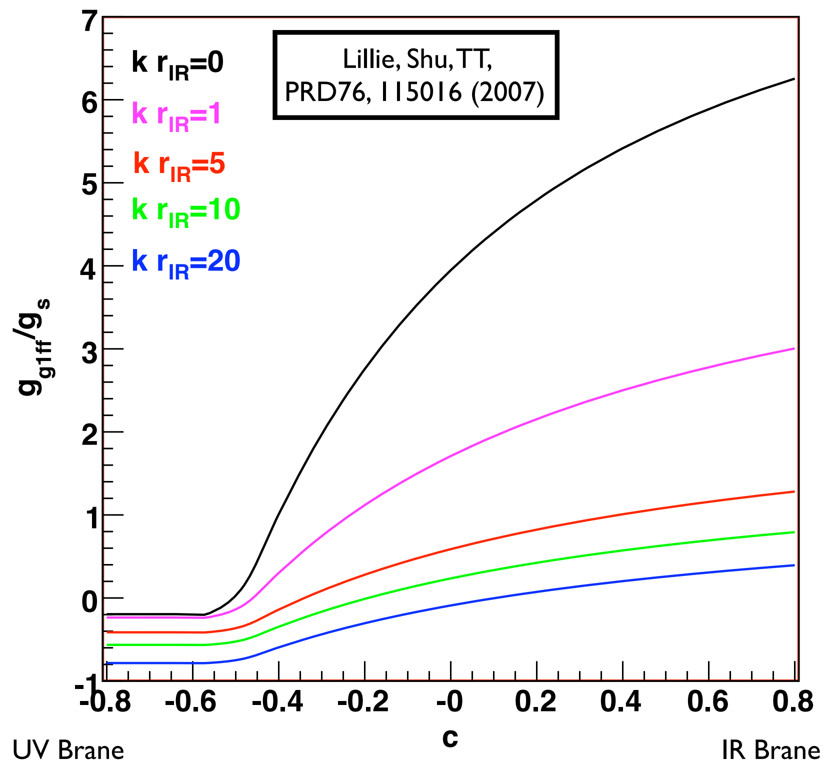
and decays into tops...

Coupling to Quarks

- In RS, there are parameters one can invoke to adjust the theory, and they leave an imprint on the couplings of quarks to the KK gluons.
- For example, we can include IR-brane kinetic terms for the KK gluon, which diminish its coupling to IR brane fields.

Davoudiasl, Hewett, Rizzo PRD68, 045002 (2003)
Carena, Ponton, TT, Wagner PRD67, 096006 (2003)

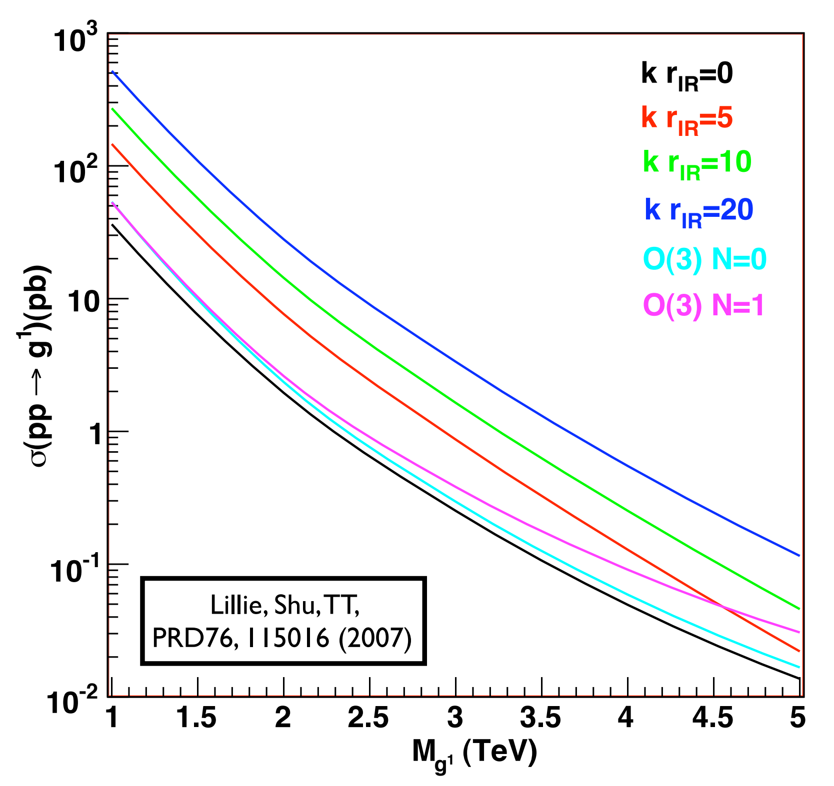
- The coupling is controlled by the quark wave functions, which are defined by a dimensionless parameter ‘c’. (Their bulk mass is c k).



Cross Sections

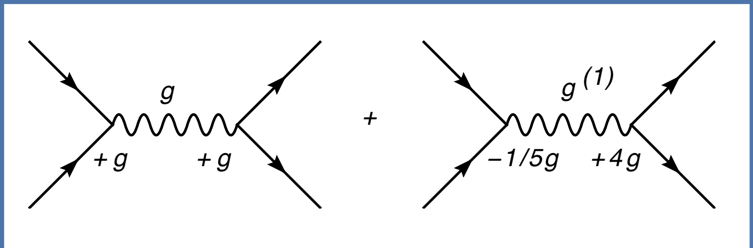
- Assuming the light quarks are mostly fundamental, the coupling to the first KK gluon is small but noticeable.
- The cross section and branching ratios depend sensitively on the couplings, and thus reflect the underlying the parameters.

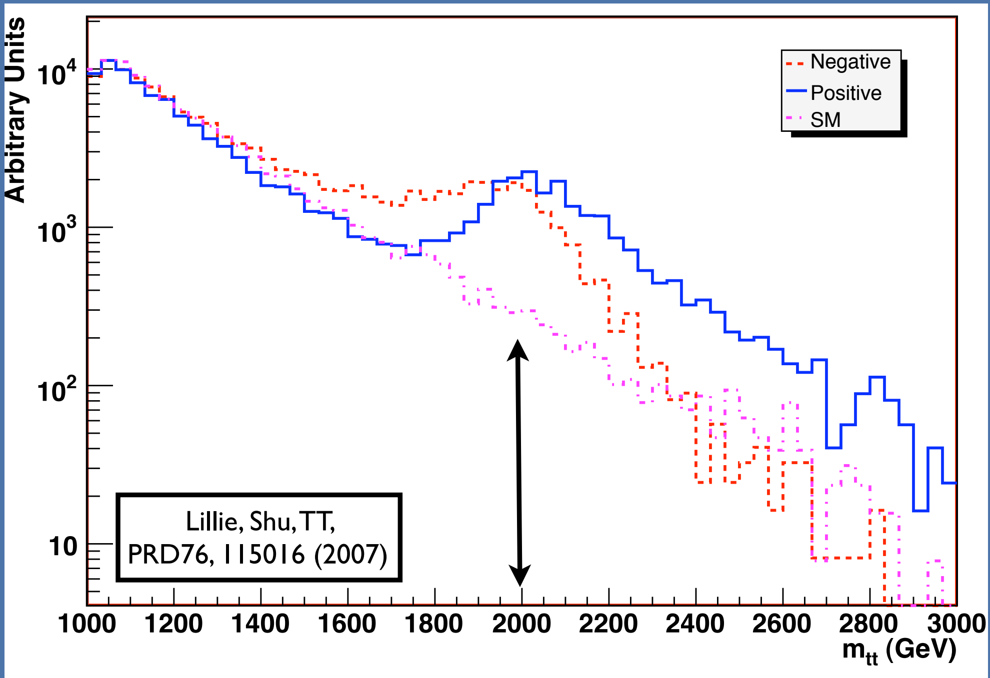
Model	top quarks	bottom quarks	light quarks	custodial partners	Γ_{g^1}/M_{g^1}
Basic RS	92.6%	5.7%	1.7%		0.14
$\kappa r_{IR} = 5$	2.6%	13.2%	84.2%		0.11
$\kappa r_{IR} = 20$	7.8%	15.1%	77.1%		0.05
$O(3),\ N = 0$	48.8%	49.0%	2.0%		0.11
$O(3),\ N = 1$	14.6%	14.6%	0.6%	70.2%	0.40



Width and Interference

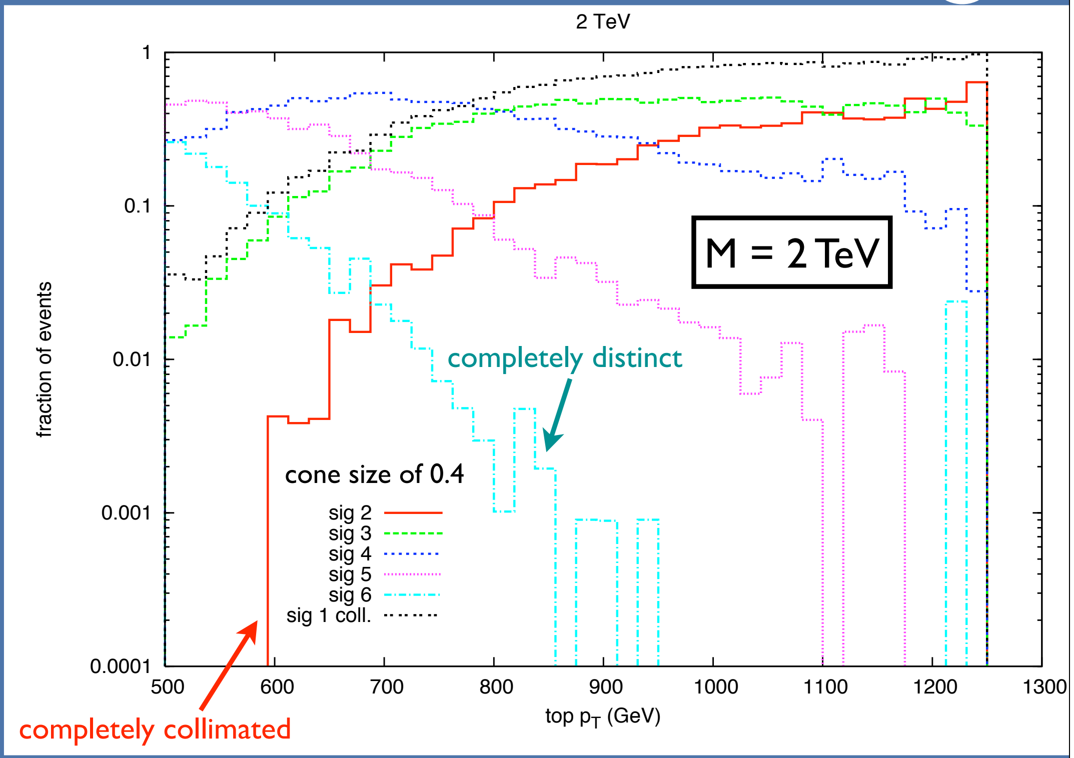
- In RS, as can be expected in any composite model, the KK gluons are strongly coupled, and have relatively large widths (~10% x M).
- The width may be directly measurable even with large LHC jet energy resolutions.
- Interference with the continuum $t\bar{t}$ background tells us about the relative sign of the couplings.





High Energy Tops

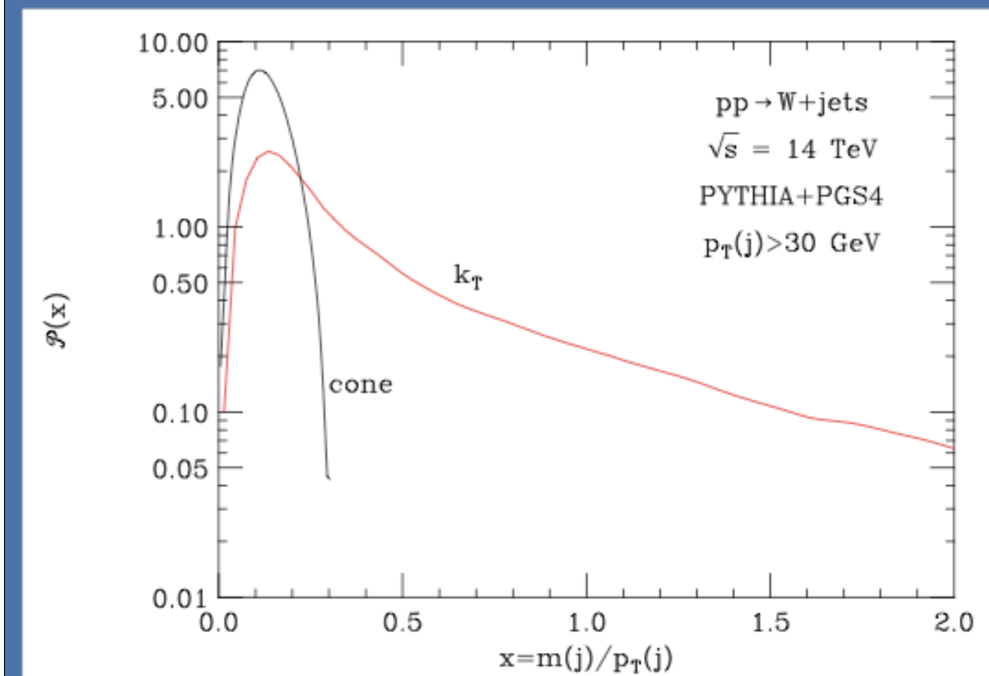
- To detect these resonances, we need to be able to reconstruct highly boosted top quarks.
- At high p_T, tops decay into more collimated jets of particles. It can be challenging to identify them as tops.
- Early studies relied on the “rare” events with enough well separated top decays, taking a hit in efficiency.



Lillie, Randall, Wang JHEP 0709:074,2007

See also: Agashe, Belyaev, Krupovnickas, Perez, Virzi, hep-ph/0612015

Jet Mass?



- Can we use the jet mass?
- The jet mass grows with p_T!
- There is strong jet algorithm dependence: kT jets tend to include more underlying event / nearby jet activity.

$$R = D = 0.5$$

cone ↗ (R)   ↖ k_T (D)

Baur, Orr, PRD76, 094012 (2007)

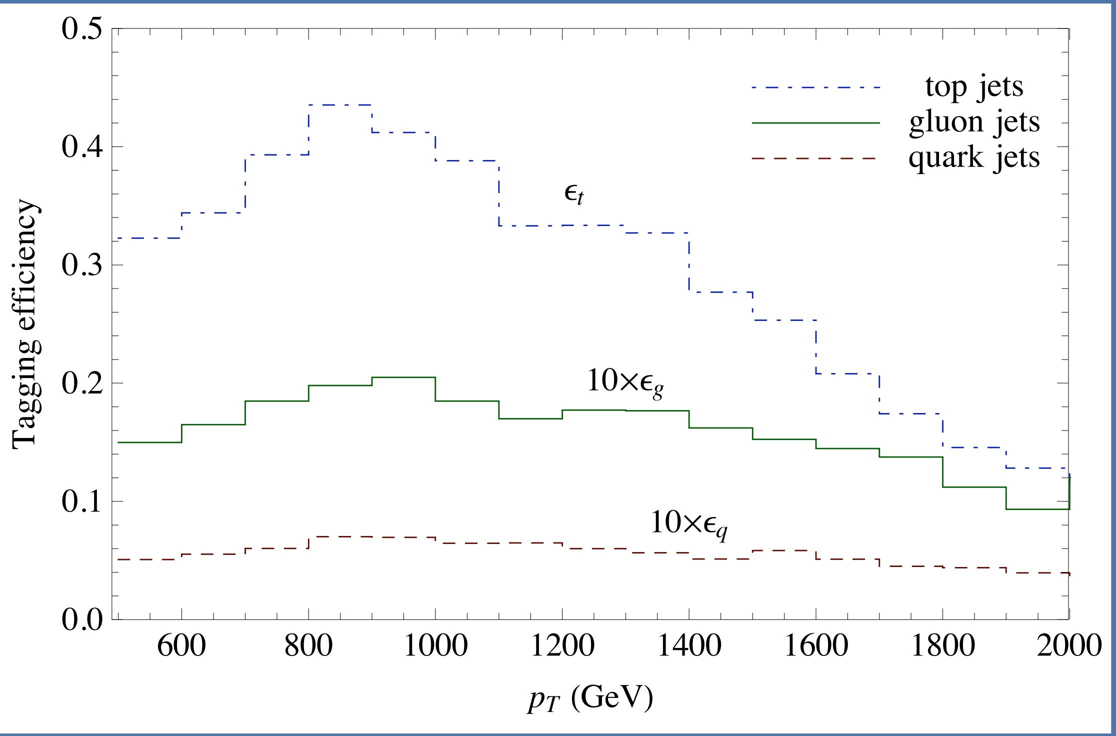
Jet Structure?

An interesting strategy is to look for internal structure inside collimated jets, to see the evidence for a boosted top decay buried inside.

Kaplan, Rehermann, Schwartz, Tweedie, PRL101, 142001 (2008)

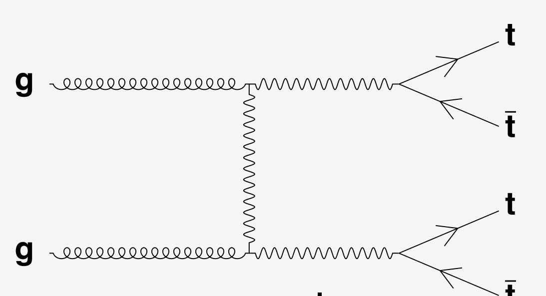
Early results are promising.

Thaler, Wang, JHEP 0807:092 (2008)
Almeida, Lee, Perez, Sung, Virzi, arXiv:0810.0934

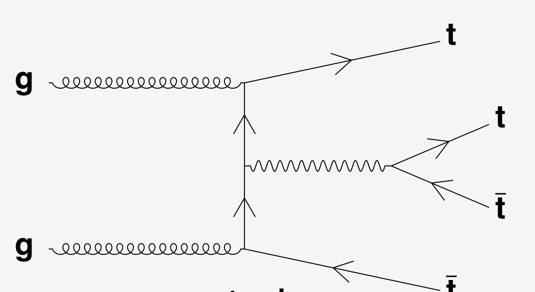


Four Tops at the LHC

- The KK gluon is a perfect resonance decaying into top pairs. But it was produced by a light quark initial state. What happens when the coupling to light quarks is too small to use as a production mechanism?
- A possible signature has color octet (and/or singlet) vectors which couple strongly to top quarks, and perhaps negligibly weakly to light quarks.
- A color octet vector can be pair-produced purely by QCD. A color singlet needs to be "radiated" from a top quark.



octet only

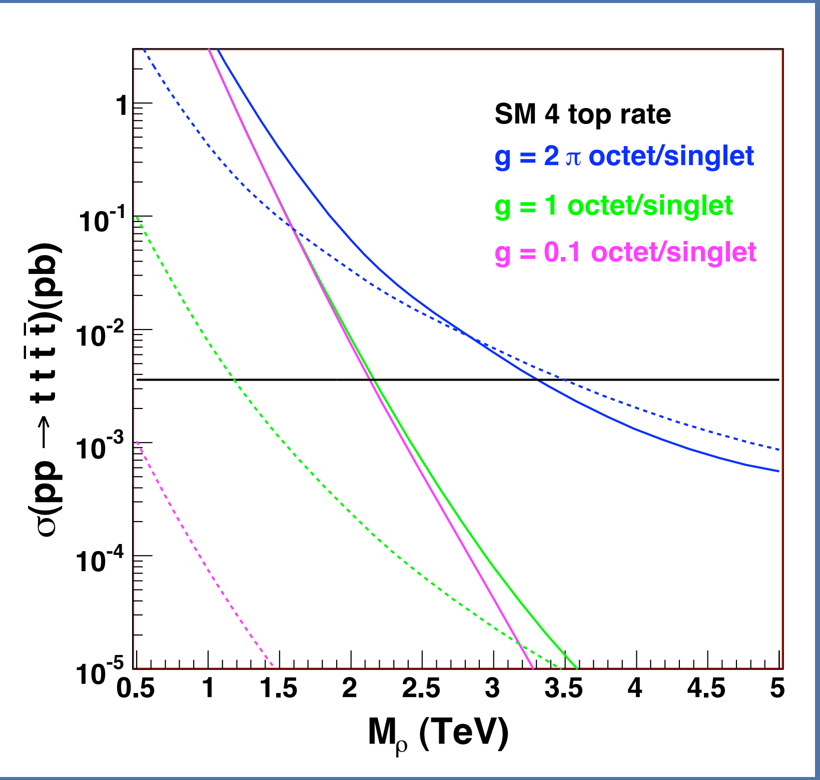


octet or singlet

Lillie, Shu, TT
JHEP 0804, 087 (2008)

Four Tops at the LHC

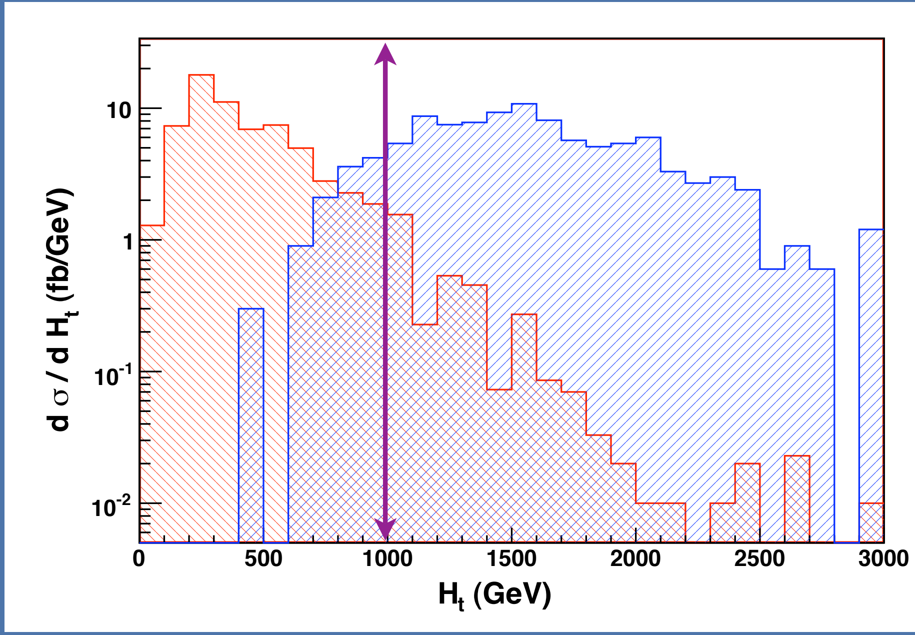
- We just saw that the color singlet is produced by being “radiated” from a top pair.
- The color octet can also be pair-produced from a gluon-gluon initial state.
- We either have one resonance plus a top pair, or two resonances.
- In either case, the resonance decays practically 100% of the time to top quarks, leading to four top signatures!



SM four top rate: a few fb.

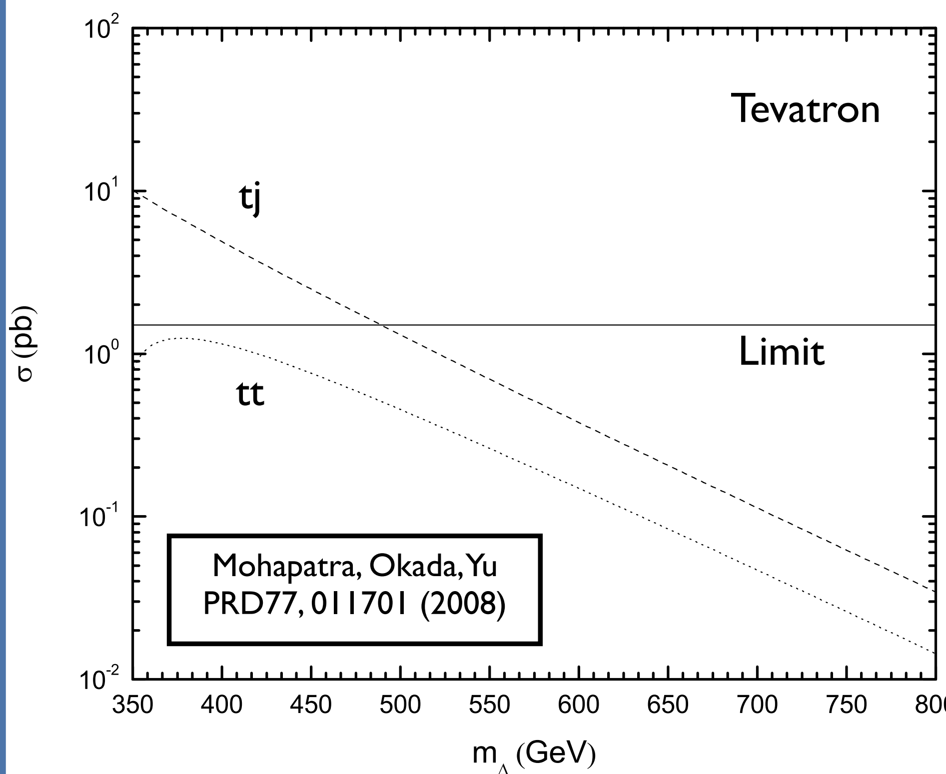
Four tops?

- So the question is: can we actually reconstruct four tops at the LHC?
- The combinatorics are highly challenging.
- One study was able to show that the decay mode with two like-sign leptons can be seen against the background with a tight cut on H_T.
- Four top rates above about 50 fb were visible against the background.



Like-sign Top Resonances

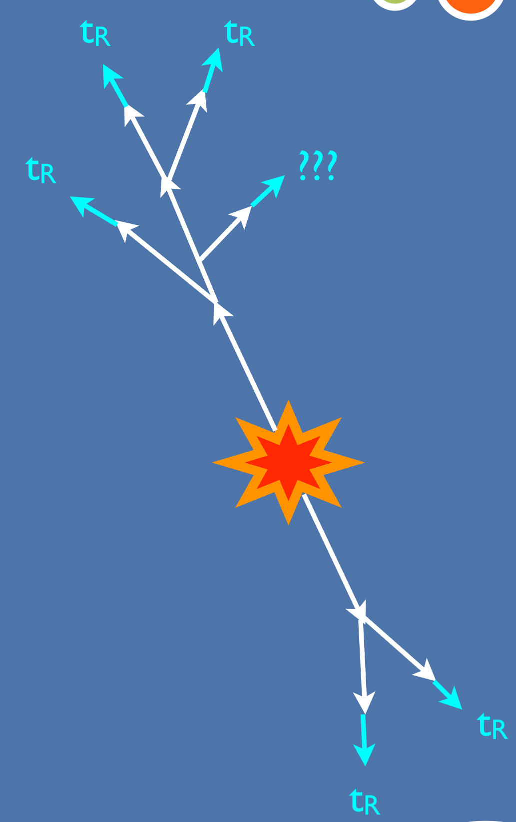
- A theory with color sextet bosons can decay into two like-sign tops, producing a novel resonance structure.
- Production can either be pairs of sextets, or single production from (say) a qq initial state.
- Pair production leads to 4 top states, but with the opposite resonance structure as we had before for an octet.



Chen, Klemm, Rentala, Wang arXiv: 0811.2105

Future Directions?

- If the top is composite, we might even be able to see its constituents directly.
- If we imagine the highest energies the LHC can probe (over the course of its life-time), even more exotic phenomena can emerge.
- For example, if we produce constituents in a regime where they are energetic and weakly coupled, maybe we can see them "hadronize" or even "shower". The result could be jets of high momentum top quarks.
- Could the LHC even reconstruct such an event? I have no idea, but it would be fun to try!



Conclusions

- Many interesting models lead to resonances that decay into top pairs. They address a wide variety of deep questions faced by particle physics.
- Top resonances challenge us to think about top in new regimes:
  - Highly Boosted tops can be collimated and hard to reconstruct as tops.
  - Multi-top processes have challenging combinatorics.
- Top may be our portal to physics beyond the SM!