Largely based on:
Lillie, Shu, TT JHEP 0804, 087 (2008)
Kumar, TT, Vega-Morales, arXiv:0901.3808

Special Topic: A Composite Top Quark?!

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Top

- In the last two days, we discussed many of the motivated reasons why top might be special, and why theories aiming to solve theoretical problems may point to it as a place to find the new physics.
- Today I will take a slightly different tack
  - Top is the quark about which we know the least. As a result, it is a place where we may find large surprises, not already ruled out by previous measurements.
  - As an example of that, I will explore the possibility that the (right-handed) top is a composite particle, and look at some of the phenomena that might result at the LHC if that were the case.

Outline

- Bounds on compositeness
  - Top compositeness : the final frontier!
  - Top pairs at the Tevatron.
- Signals at the LHC
  - Resonances
  - Four top signals
- Outlook and future directions.

Can we see Compositeness at the LHC?

Compositeness?

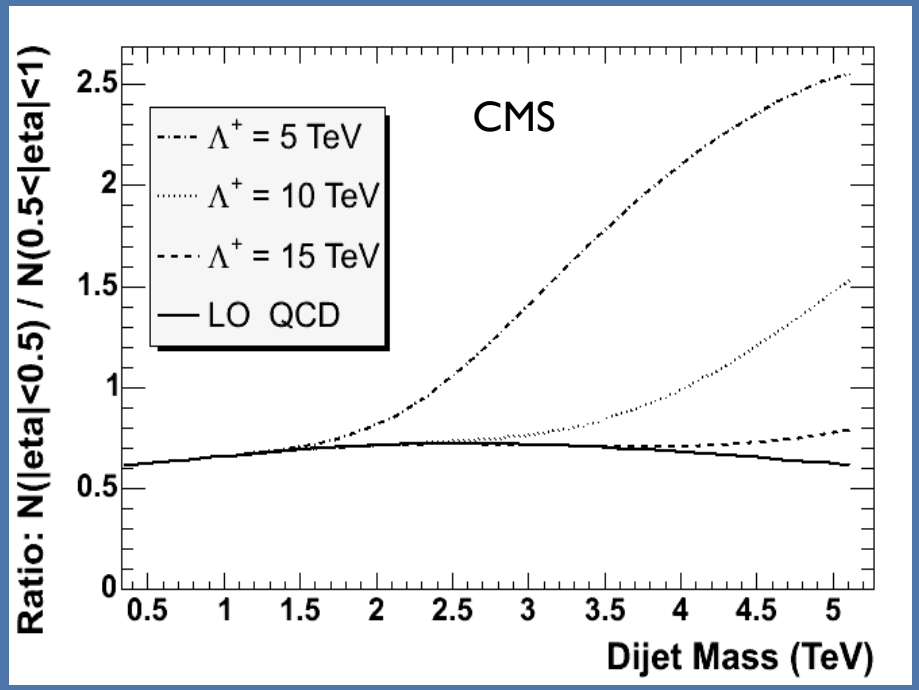
- A better first question would be to explain what I mean when I say "compositeness".
  - The physical picture I have in mind is that some or all of the fields of the Standard Model might be revealed to have internal structure.
  - A good picture is the proton: from far away, it looks point-like, but up close it is made out of quarks.
  - If the SM fields were weakly bound states, we would notice, because it would be relatively easy to rip them apart.
  - So I will focus on the case when some of the SM fields are strongly bound states, arising from some new confined force.

The quick answer is...

Yes.

Using the Eichten-Lane-Peskin parameterization in terms of higher dimensional operators, the LHC will probe (some) operators up to scales of order 10's of TeV.

$$\frac{g^2}{\Lambda^2}\left[\bar{q}\gamma^\mu q\right]\left[\bar{q}\gamma_\mu q\right]$$

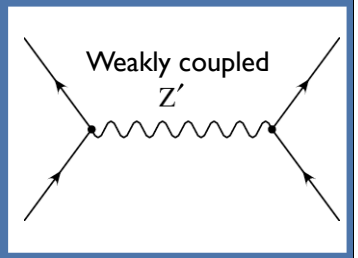


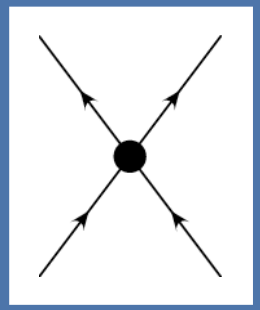
Eichten, Lane, Peskin PRL50, 811 (1983)

Wow!

That's great, but...

Higher dimensional operators are as much a sign of compositeness as they are of any kind of high scale new physics. We tend to refer to them as coming from compositeness mostly because we have no idea what else to do with compositeness.





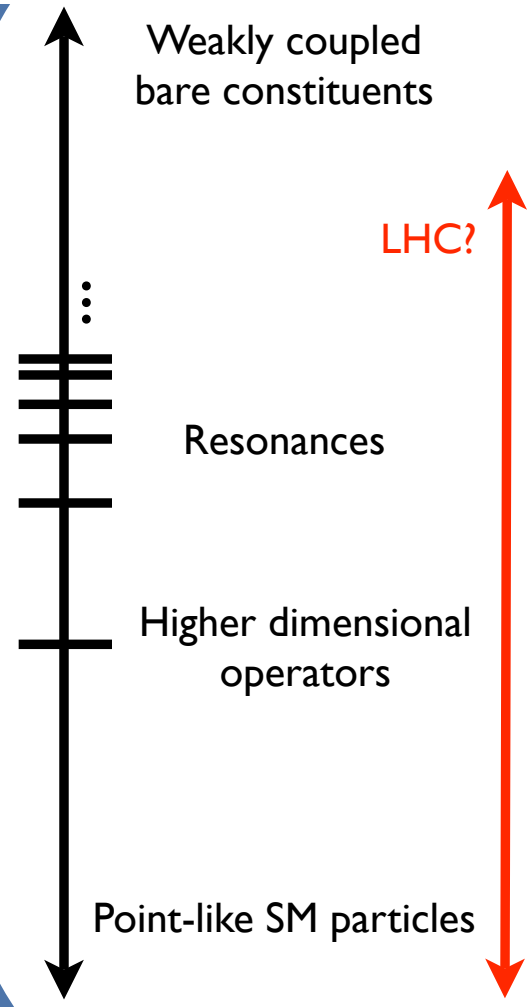
It would be even better to see some phenomena which we could associate with compositeness and not other types of new physics.

Constituents

- If the SM is partially or completely composite, we should identify the known particles with the lightest of the composites - the "pions".
- Beyond contact interactions, we could look for:
  - Higher resonances - the "rhos", "nucleons", etc...
  - Constituents - the "quarks".
- The question is :"Does the Standard Model work so well that we can already guess that there is no hope to see the constituents at the LHC?"

Seeing Constituents?

- We know the LHC can discover higher dimensional operators up to large Λ.
- We also have examples of composite theories (RS, Technicolor) for which it can also discover at least the first layer of the higher resonances. If quarks are composite, some of the resonances should be colored, which helps produce them.
- Standard RS is not a good example to imagine going further than mapping resonances, because its approximate scale invariance implies the resonance description works up to ~ its UV cut-off which we usually take near M_{Pl}.



Constraints

- Using the existing constraints on contact interactions we can (at least roughly) answer the question.

for example: $$\frac{g^2}{\Lambda^2}\left[\bar{q}\gamma^\mu q\right]\left[\bar{q}\gamma_\mu q\right]$$

- Any sector for which $\Lambda >> E_{LHC}$ will be very difficult for the LHC to resolve at the level of constituents.

- A sector for which $\Lambda \sim E_{LHC}$ will potentially be visible (at least we can hope for a few resonances).

What I'll do now is run through different sectors of SM and assess the (rough) compositeness bounds on each one.

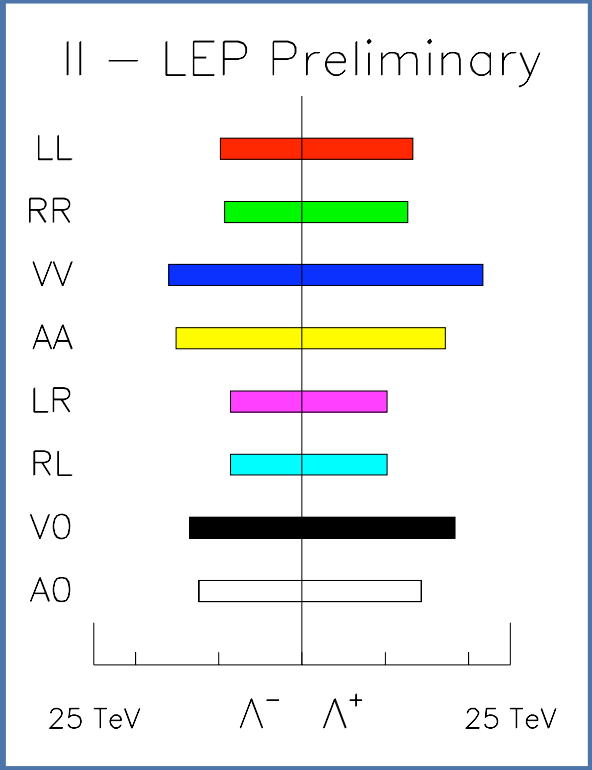
Leptons at LEP-II

The LEP EWWG uses LEP-II data to put strong bounds on operators involving leptons.

$$\frac{4\pi}{(1+\delta)\Lambda^2} \sum_{i,j=R,L} \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

Their analysis derives a limit of about $\Lambda \gtrsim 10 \text{ TeV}$.

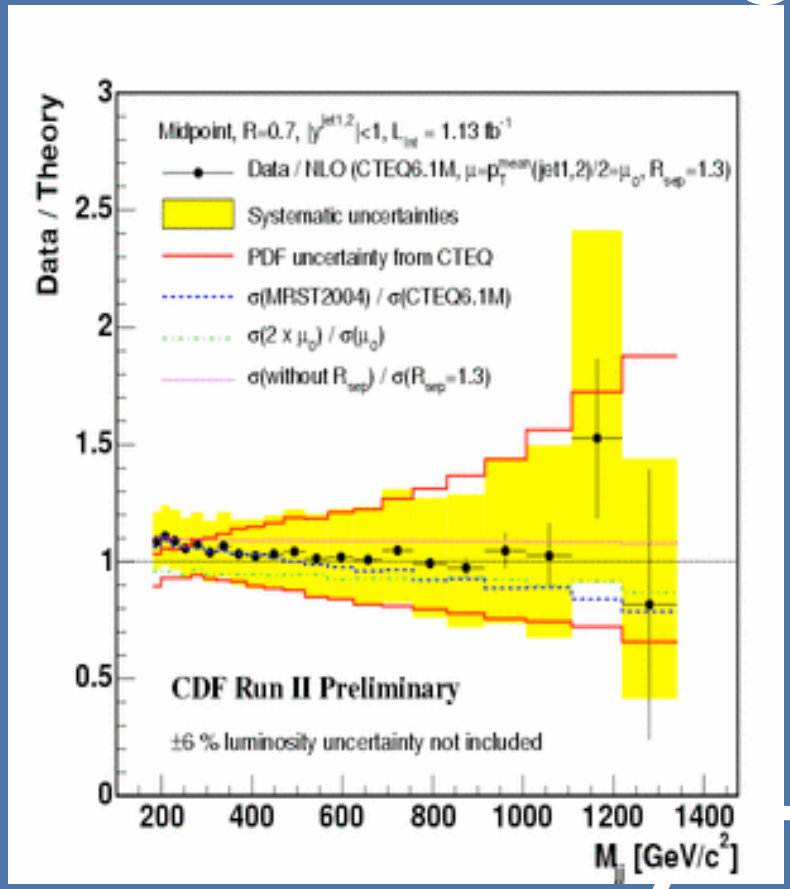
$$\delta = \begin{cases} 1 & f = e \\ 0 & f \neq e \end{cases}$$



Light Quarks at Tevatron

- Operators involving four light quarks can contribute to dijet production.
- Neither CDF nor D0 has run II published limits on contact interactions, though one can estimate their size from the data.

$$\sigma \simeq \sigma_{SM}\left(1+(4\pi)^2\frac{E^2}{\Lambda^2}\right)$$



$$\Lambda \gtrsim 5 \text{ TeV}$$

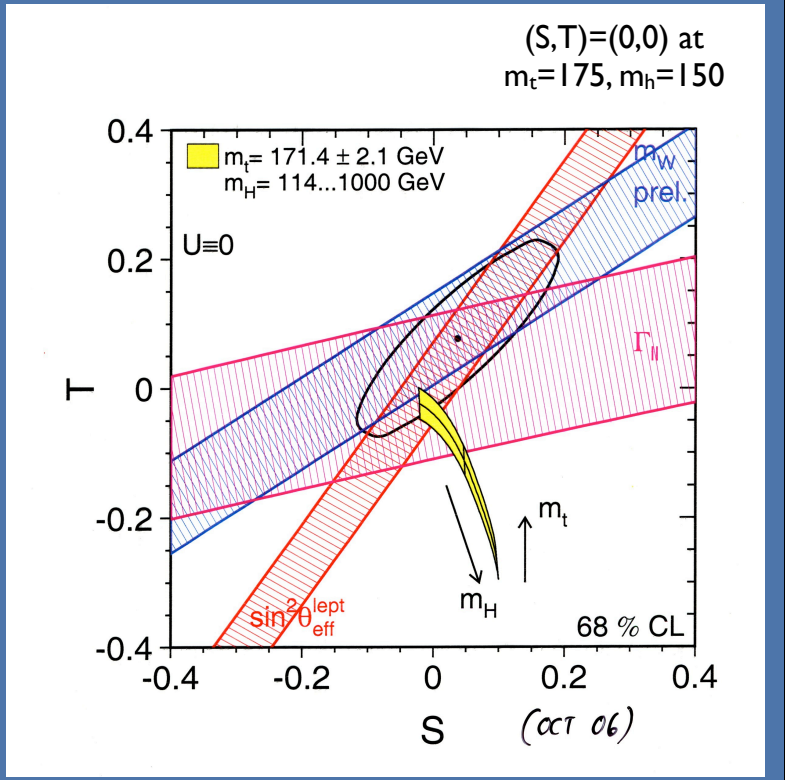
Higgs at LEP/SLD

- Precision EW measurements limit Higgs operators.
  - Custodial isospin violating (T-parameter)

$$\Lambda \gtrsim 30 \text{ TeV}$$

  - Custodial isospin preserving (S-parameter)

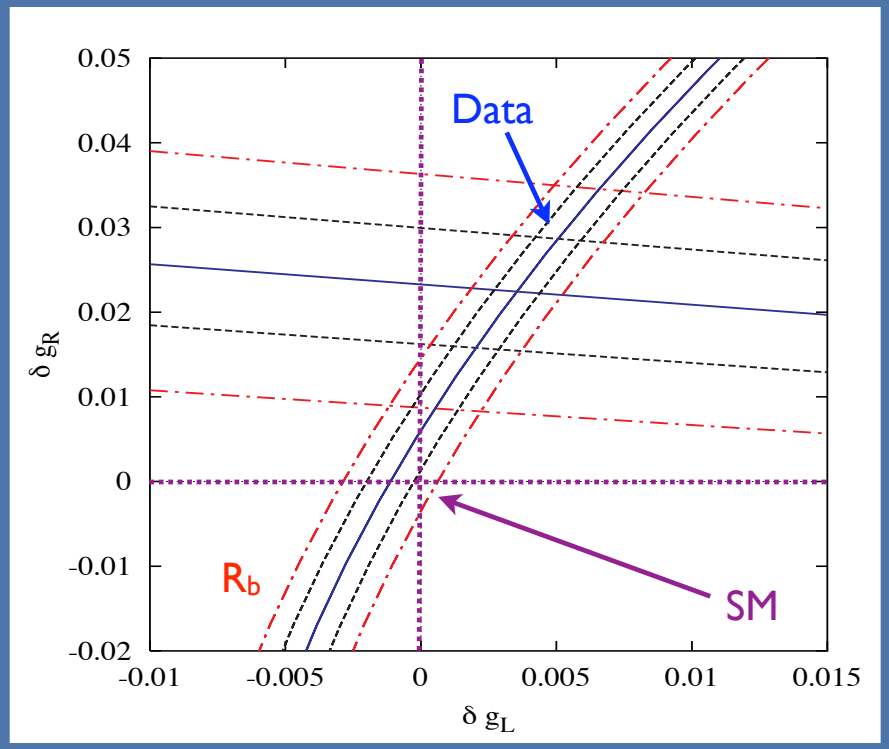
$$\Lambda \gtrsim 3 \text{ TeV}$$



Heavy Quarks

- Precision Electroweak measurements also limit the deviations allowed in the bottom sector.
- Which also limits the scale of compositeness possible for the left-handed top.
- b_R is more subtle, because of the A_b^{FB} puzzle.

Data



Choudhury, Wagner, Tait PR65, 053002 (2002)

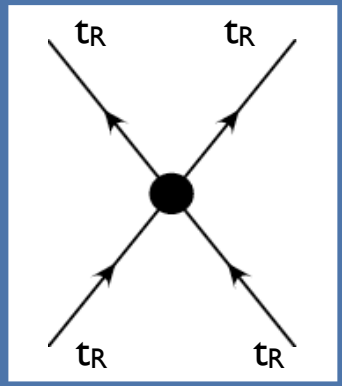
$$\Lambda \gtrsim 5 \text{ TeV}$$

Leaving...

- ...the right-handed top quark!
- The operator with four right-handed tops has a unique Lorentz structure, and several options for color structures.

$$\frac{g^2}{\Lambda^2}[\bar{t}^i\gamma^\mu P_R t_j][\bar{t}^k\gamma_\mu P_R t_l]$$

Georgi, Kaplan, Morin, Schenk PRD51, 3888 (1995)



- Two interesting color structures are a pair of singlets and octets.

$$\delta_i^j\delta_k^l \qquad (T^a)_i^j(T^a)_k^l$$

The 4-t_R Operator

- Even independently of any other interest, it is interesting to ask what are the bounds on this family of 4-top operators.
- Insertions of this operator into precision EW observables (closing it into a loop) turn out to result in corrections of order the errors on S and T extracted from data, so not very strong constraints.
- The best bound turns out to come from top pair production at the Tevatron.

Tevatron Bounds

- We'd like to use Tevatron data about top to find out how strong the bounds are - this will tell us whether the LHC has some hope to see constituents, or will have to be content to look for resonances.

- The 4-top operator is difficult to bound at the Tevatron. The natural thing to look for is four top production, but at Tevatron energies that process is negligible. What we need is a contribution to top pair production.

- So we look at operators which modify the top coupling to quarks & gluons:

$$\frac{g_1 g_s}{\Lambda^2} H\,[\bar{t}\sigma^{\mu\nu}T^a t]\,G^a_{\mu\nu} \quad \frac{g_2 g_s}{\Lambda^2}\,[\bar{t}\gamma^\mu D^\nu P_R t]\,G^a_{\mu\nu} \quad \frac{g_3 g_s}{\Lambda^2}\,[\bar{t}\gamma^\mu T^a P_R t]\sum_q [\bar{q}\gamma^\mu T^a q]$$

- In the compositeness picture, these operators represent hard gluons which probe the internal structure of the top, seeing the motion of the colored preons inside it.

Buchmuller, Wyler NPB 268, 621 (1986)
Atwood, Kagan, Rizzo PRD52, 6264 (1995)
Hill, Parke PRD49, 4454 (1994)

Top Pairs

- Naive dimensional analysis suggests the sizes for these operators at scale Λ:

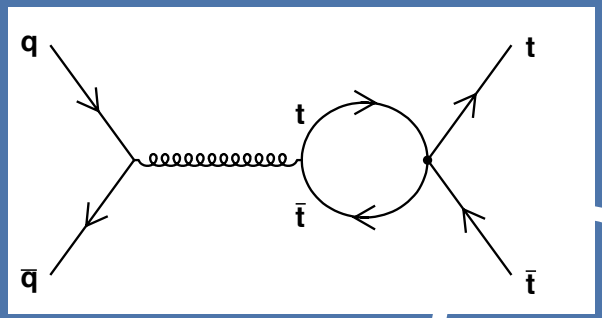
$$g_1(\Lambda) \sim \frac{1}{g} \qquad g_2(\Lambda), g_3(\Lambda) \sim 1$$

- The second operator is induced from the 4-top operator through the RGEs.
- The third operator is related through the equations of motion to the second operator plus its Hermitean adjoint. Thus, we can set $g_3=0$ at the cost of shifting the real part of g_2.
- We allow general complex g_1 and g_2 in our analysis of top pair production.

$$\frac{g_1 g_s}{\Lambda^2} H \left[\bar{t}\sigma^{\mu\nu}T^a t\right] G^a_{\mu\nu}$$

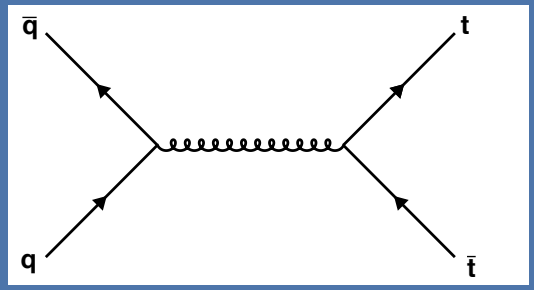
$$\frac{g_2 g_s}{\Lambda^2} \left[\bar{t}\gamma^\mu D^\nu P_R t\right] G^a_{\mu\nu}$$

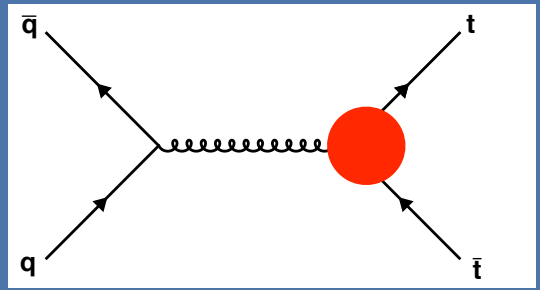
$$\frac{g_3 g_s}{\Lambda^2} \left[\bar{t}\gamma^\mu T^a P_R t\right] \sum_q \left[\bar{q}\gamma^\mu T^a q\right]$$



Top Pairs

- We neglect the gluon fusion contribution, which is a bit less than 15% or so at the Tevatron.
- The dominant correction arises from the new physics amplitudes interfering with the Standard Model.
- We can write the partonic cross section to order $1/\Lambda^2$ as a correction to the SM prediction:



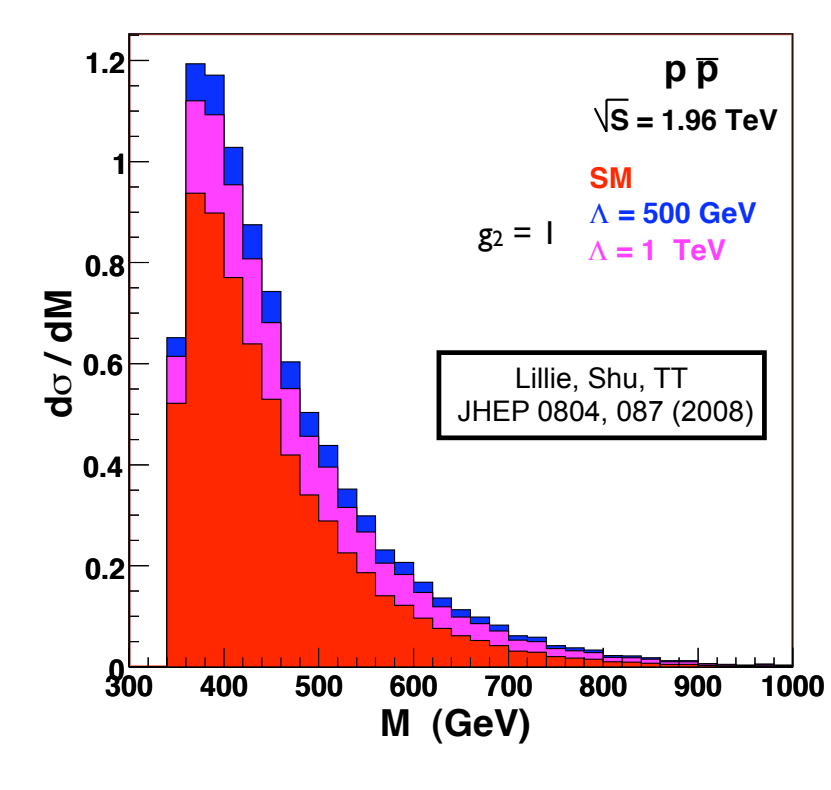


$$\hat{\sigma} = \sigma_{\hat{S}M}\left(1 + \ \mathrm{Re}\ \frac{g_1(16vms^2) + g_2(4m^2s^2 + s^3 + s(s+2t-2m^2)^2}{2\Lambda^2(2m^4 + s^2 - 4m^2t + 2st + 2t^2)}\right) + O\left(\frac{1}{\Lambda^4}\right)$$

- The relative correction grows with energy compared to the SM, and modifies invariant mass and production angle distributions.

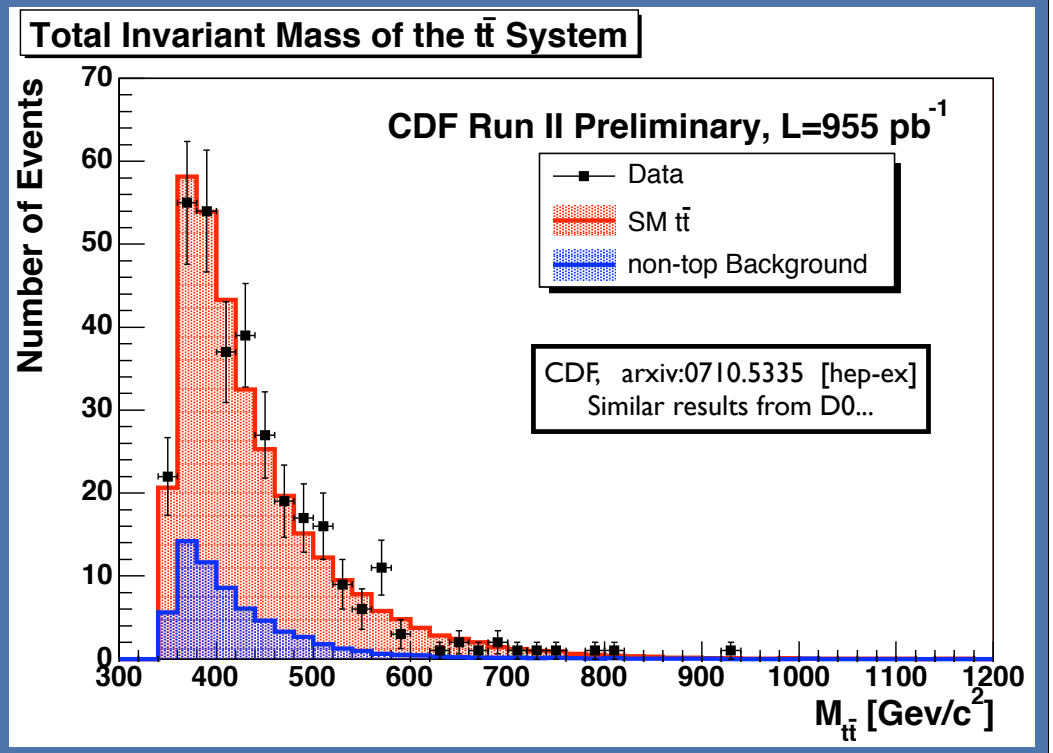
Invariant Mass Distribution

- An obvious way to get a bound is to study the invariant mass of top pairs. The four top operator causes it to fall off less quickly with M than the SM prediction (or causes a deficit).
- The distribution shown is LO, and includes the (modified) $q\bar{q}$ initial state and (unmodified) gg initial state. The SM rate was generated at the parton level with MadEvent, and then the new physics was added by hand.



$M_{t\bar{t}}$

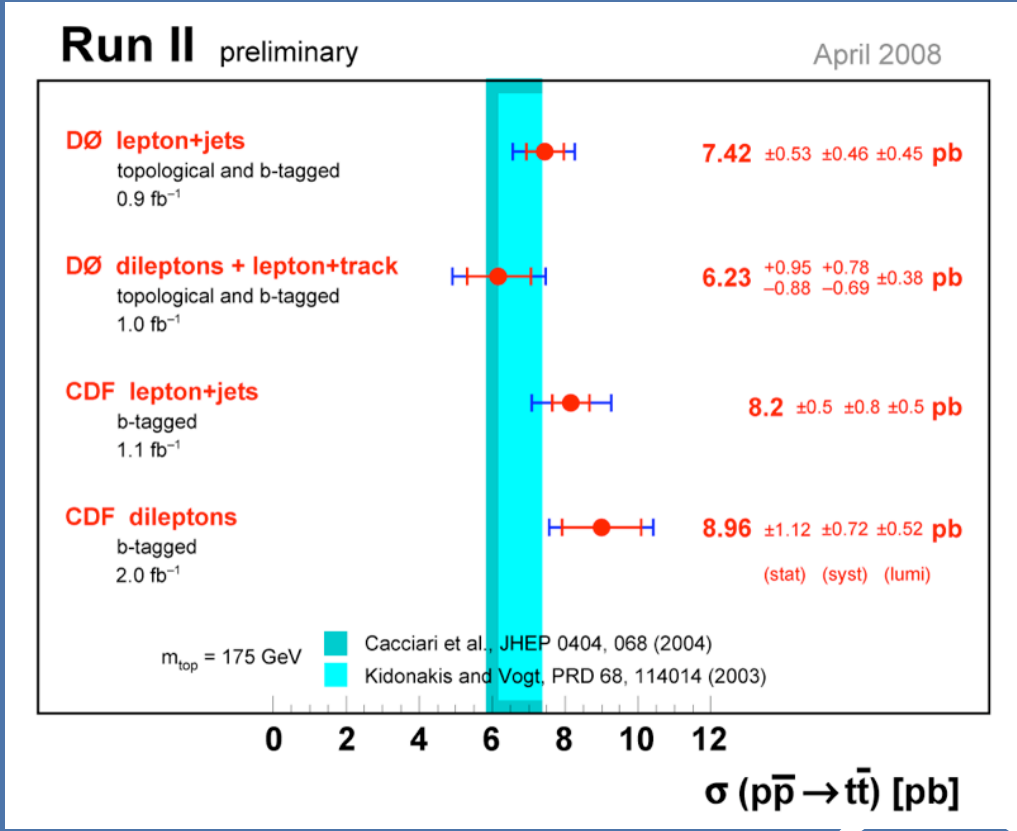
- CDF and D0 both have results for top pairs binned in the invariant mass.
- It's not in a form that is immediately useful for a theorist, because it includes efficiencies and some non-top backgrounds.
- However, clearly there is good agreement between the theory expectation and the data.



This analysis puts a bound on narrow resonances decaying to top pairs.

Total Cross Section

- Since the invariant mass distribution is difficult to extract, I can at least ask that the impact on the total cross section be within the experimental errors.
- Both CDF and D0 have consistent measurements, slightly on the high side of the best theory estimates (but consistent within error bars).



Bounds

- Taking the most precise measurements:

$$\sigma_{exp} = 7.0 \pm \underset{\text{(statistical)}}{0.3} \pm \underset{\text{(systematic)}}{0.4} \pm \underset{\text{(luminosity)}}{0.4} \text{ pb}$$

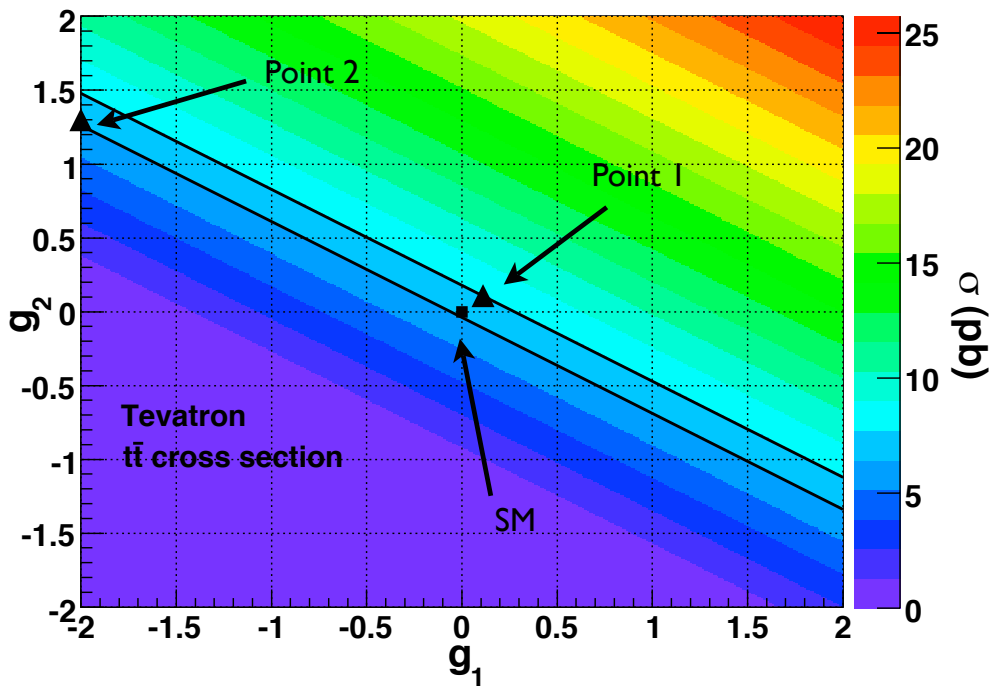
- Compared with the theory prediction:

$$\sigma_{SM} = 6.6 \pm 0.8 \text{ pb}$$

Kidonakis, Vogt Eur Phys J C 33 S466 (2004)
Mangano, Nason, Ridolfi JHEP0407, 033 (2004)

- We fix Λ = 500 GeV and compute the rate for different values of g_1 and g_2.

Re g_1 - Re g_2 Plane



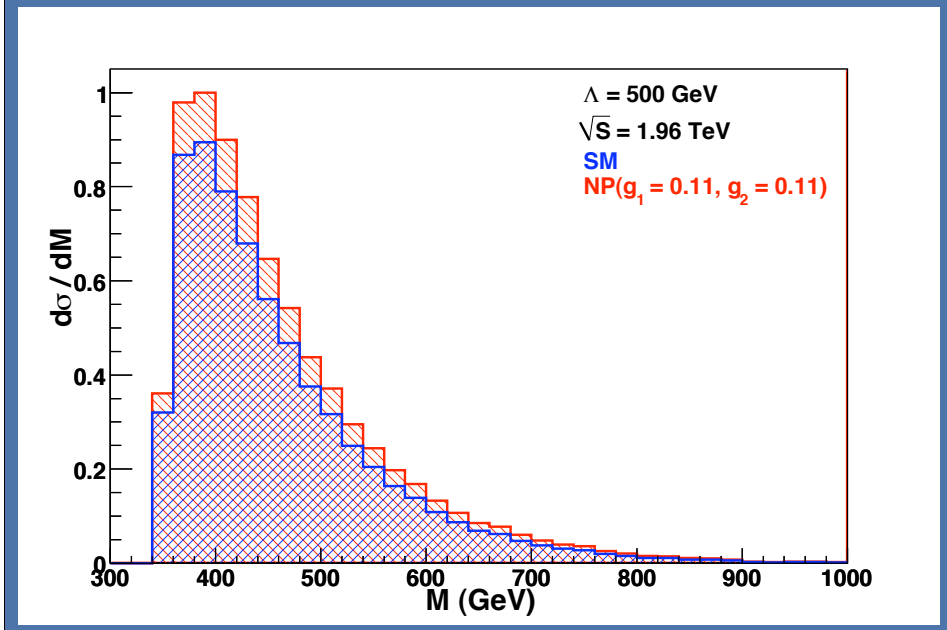
Λ = 500 GeV

A swath of the g1-g2 plane is consistent with measurements.

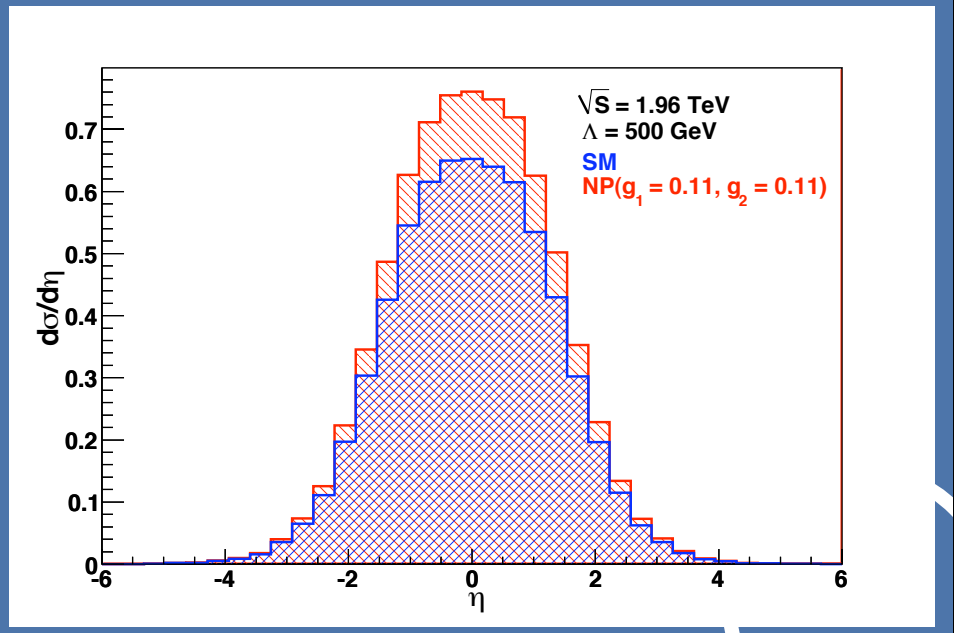
In particular, if g1 and g2 take opposite signs, the effects of the two operators may partially cancel in the net cross section.

To illustrate the importance of distributions in going further, we consider two points consistent within one σ for the cross section.

Point 1

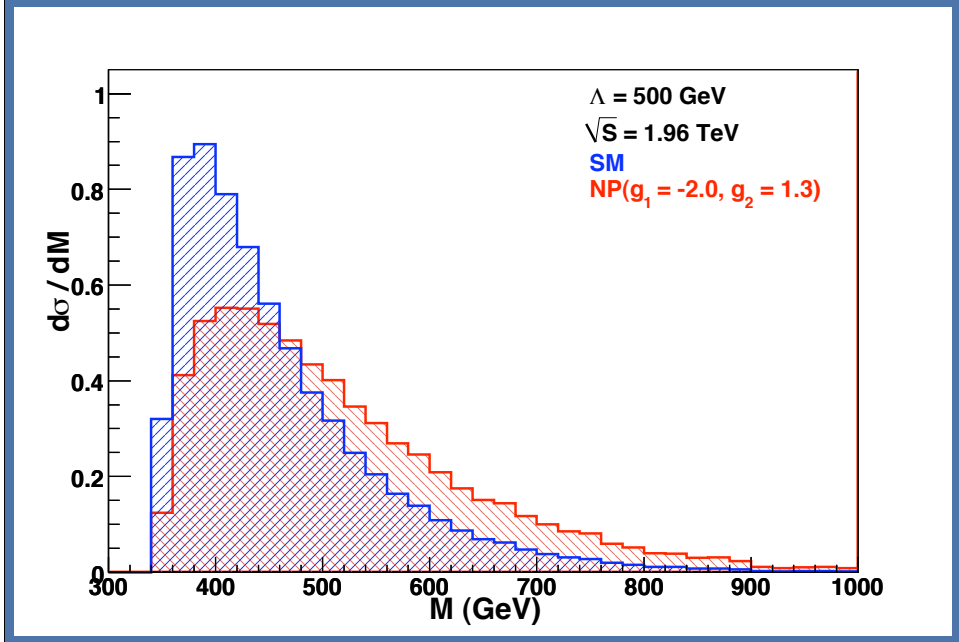


Point 1 has no cancellations in the rate. The effects on distributions are modest.



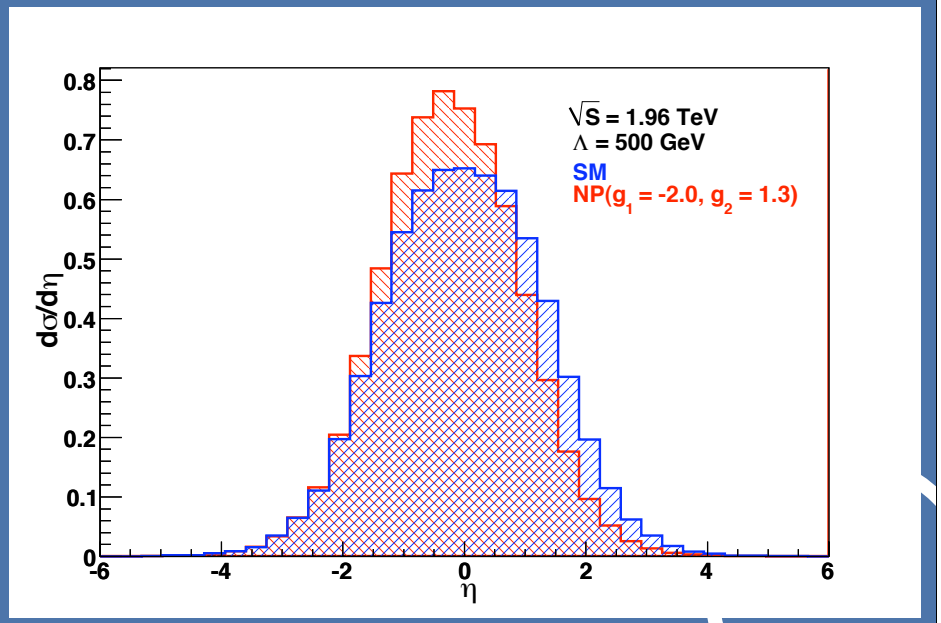
The top invariant mass distribution is shifted to slightly higher energies. The top rapidity distribution is a little more central.

Point 2



Point 2 has modest cancellations in the rate. The effects on distributions are pronounced.

The top invariant mass distribution is very shifted. The top rapidity distribution is noticeably asymmetric. (But not enough to explain the CDF measurement...)

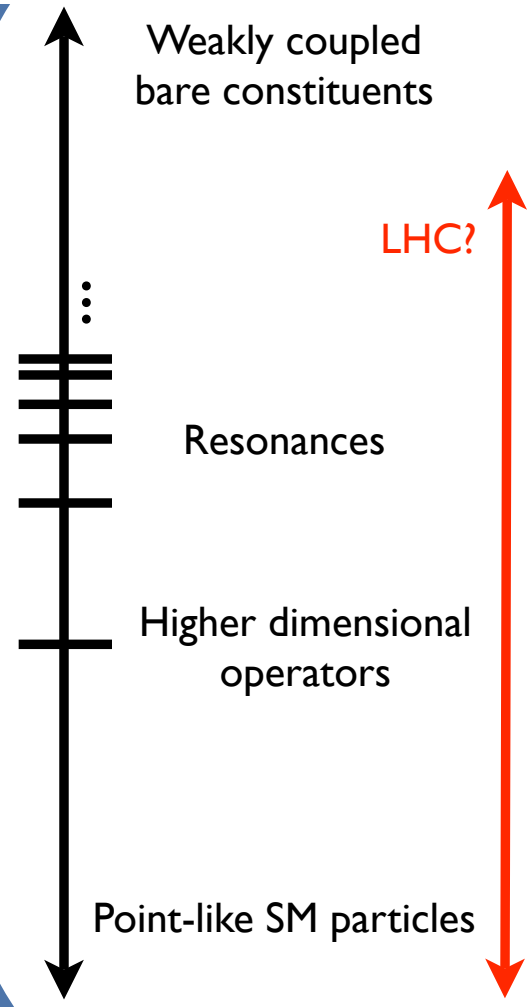


Tevatron Conclusions

- Order one values of the g's and Λ of about 500 GeV can be consistent with the rate of top pair production.
- One can do better with distributions, but it is beyond the scope of what a theorist can easily do with the available data.
- Nonetheless, it is clear that compositeness scales of roughly 500 GeV are allowed by Tevatron data, with g's a little smaller than order one.
- This implies the possibility of large effects, including potentially the ability to see constituents at LHC energies.
- In the remaining time, I will explore some possible LHC signals of a composite top.

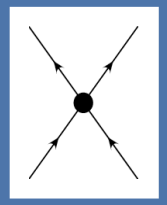
Next Stop: Resonances

- We've now learned from Tevatron data that the bounds on the higher dimensional operators require the scale Λ to be of order several hundred GeV.
- The next thing to do is to explore some of the higher resonances we might see.
  - Heavy copies of the top itself
  - Other resonances made out of the same ingredients we can imagine were needed to make a composite top.
- I'll explore the second option, and focus on vector particles - the "rho mesons".

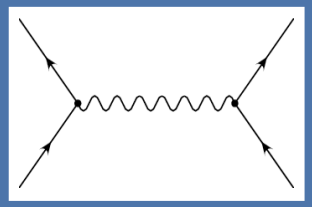


Mapping to Resonances

- If the top is composite, some of the constituents should be colored. So a color octet vector meson is a typical element of the "higher resonances".
- Even so, mapping the constraint on the operator to the properties of the vector is still model dependent...
  - How many resonances?
  - How strongly coupled are they?
  - Is a single resonance a good description at all?
    - Perhaps we need a momentum-dependent form-factor $f(p^2)$?



$$\sim \frac{g^2}{M_V^2} \; ?$$

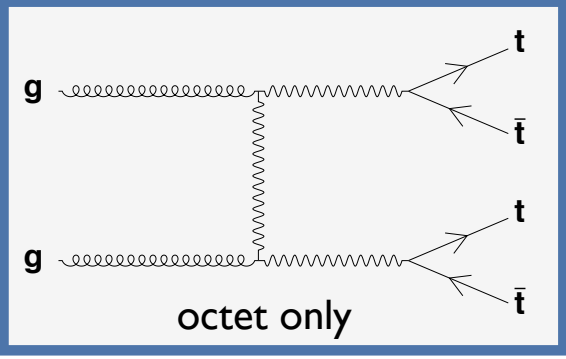


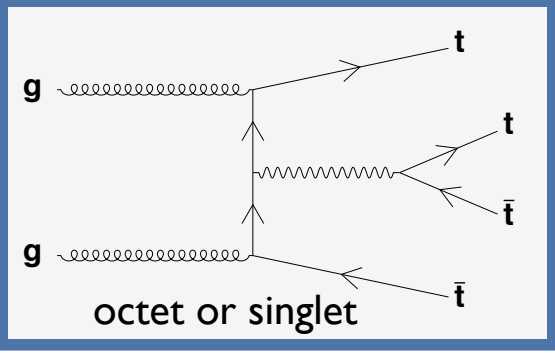
- To go forward, I'll assume moderately strong coupling and that the bound is dominated by a single vector boson.

I'll consider both color octet and color singlet vector resonances.

Four Tops at the LHC

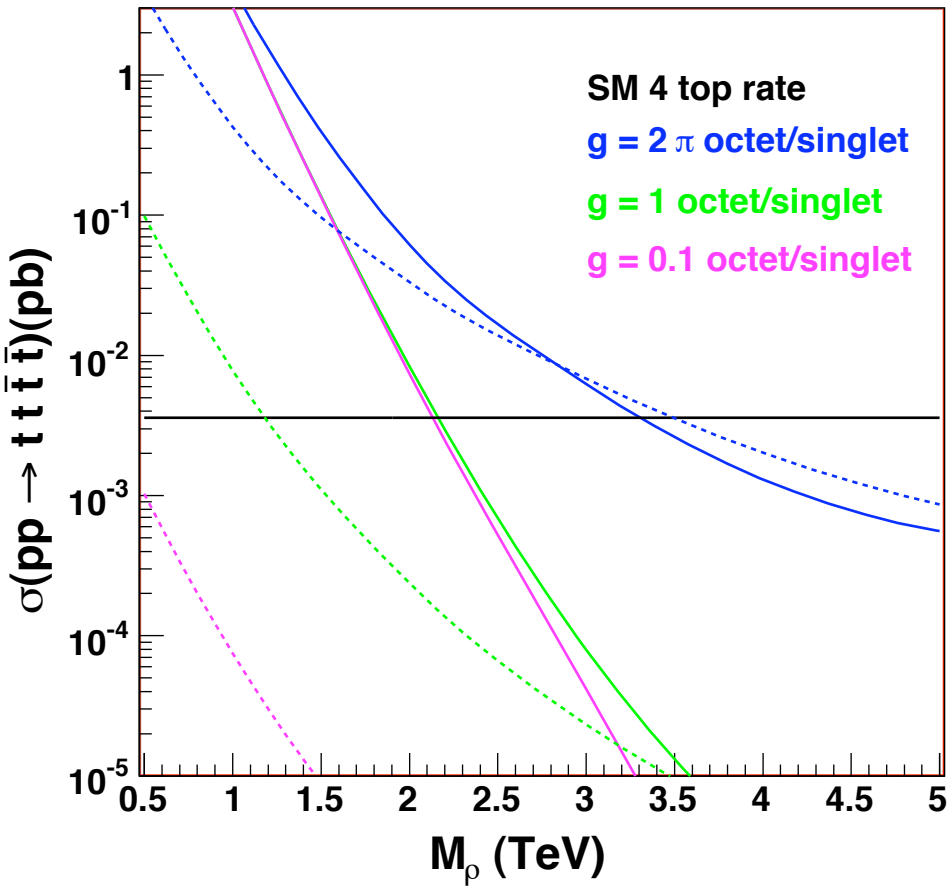
- A generic model has color octet (and/or singlet) vector particles which couple strongly to top quarks, and perhaps negligibly weakly to light quarks. The feature of negligible coupling to light quarks is quite distinct from, i.e. RS models with KK gluons.
  - When the coupling to light quarks is too small, we cannot use it as a production mechanism to produce a resonance in top pairs.
- A color octet vector can be pair-produced purely by QCD. A color singlet needs to be "radiated" from a top quark.





Four Top Cross Sections

- Our resonances decay practically 100% of the time into top quarks, leading to a four top signal.
- The cross sections for octets and singlets show a very different dependence on the coupling of the resonance to top quarks.
- The SM four top rate is very small : a few fb.



Four tops?

- So the question is: can we actually reconstruct four tops at the LHC?
- A recent study concluded we can, but used a jet mass technique which is probably very sensitive to underlying event and mis-measurement.

Gerbush, Khoo, Phalen, Pierce, Tucker-Smith arXiv:0710.3133 [hep-ph]

- We went with a more conservative approach, and required two like-sign leptons (either electron or muon) together with 2 or more hard jets.
- After showing we can extract the signal from the background, we can ask additional questions to show it looks "4 top-like".

Backgrounds

- The backgrounds we simulate as part of the hard process are:
  - $W^{\pm}W^{\pm}$ + 2 jets .
  - $W^{\pm}Z$ + 2 jets.
  - $W^{\pm}$ + $b\bar{b}$ + jet with a semi-leptonic b decay. single top!
  - $W^{\pm}$ + 3 jets with a jet faking a lepton.
  - $W^{+}W^{-}$ + 2 jets ($t\,\bar{t}$) with a charge mis-identified or a hard isolated lepton from a b decay.

Simulation

- We simulate the hard processes using MadEvent.
- We run the events through PYTHIA to decay the tops and Ws, and to shower and hadronize the partons.
- We use PGS with the default LHC detector simulation to estimate the detection efficiency, reconstruct jets, etc.

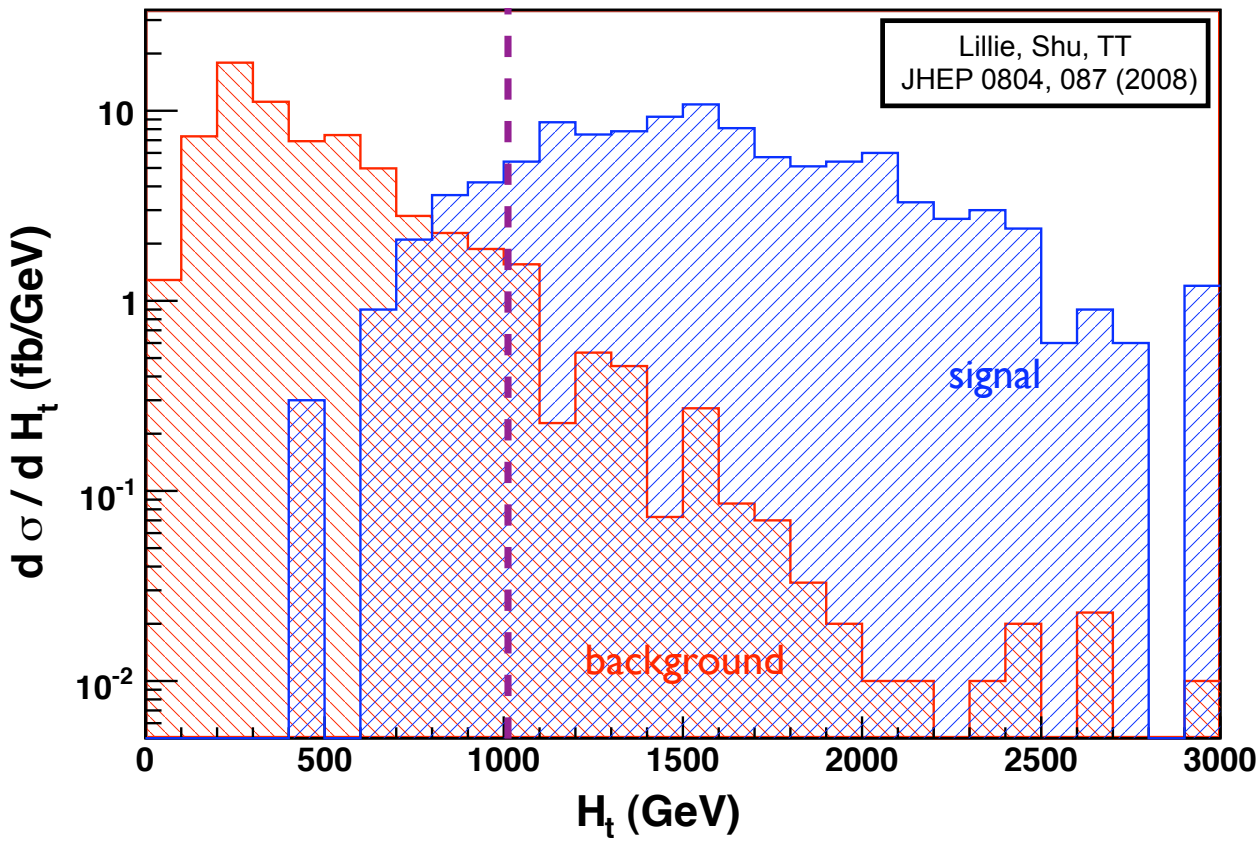
Our point is not to do a fully realistic study, but to do a reasonable "back of the envelope" demonstration that the signal is feasible.

- The exception is the W + 3 jets background, which we cut at the parton level and apply a mistag rate of 10^{-4}, after which it is small (but not negligible).

Cuts

- We require two same-sign leptons, either electrons or muons with $p_T > 30$ GeV, $|y| < 2.5$.
  - This should be good enough to trigger ATLAS.
- Two jets with $p_T > 20$ GeV, $|y| < 2.5$.
- To help with the semi-leptonic b-decays, we impose a jet isolation cut around both leptons of $\Delta R > 0.2$.
- To get high energy events which have the possibility to correspond to 4 tops, we require $H_t > 1$ TeV.

H_t Distribution



Backgrounds

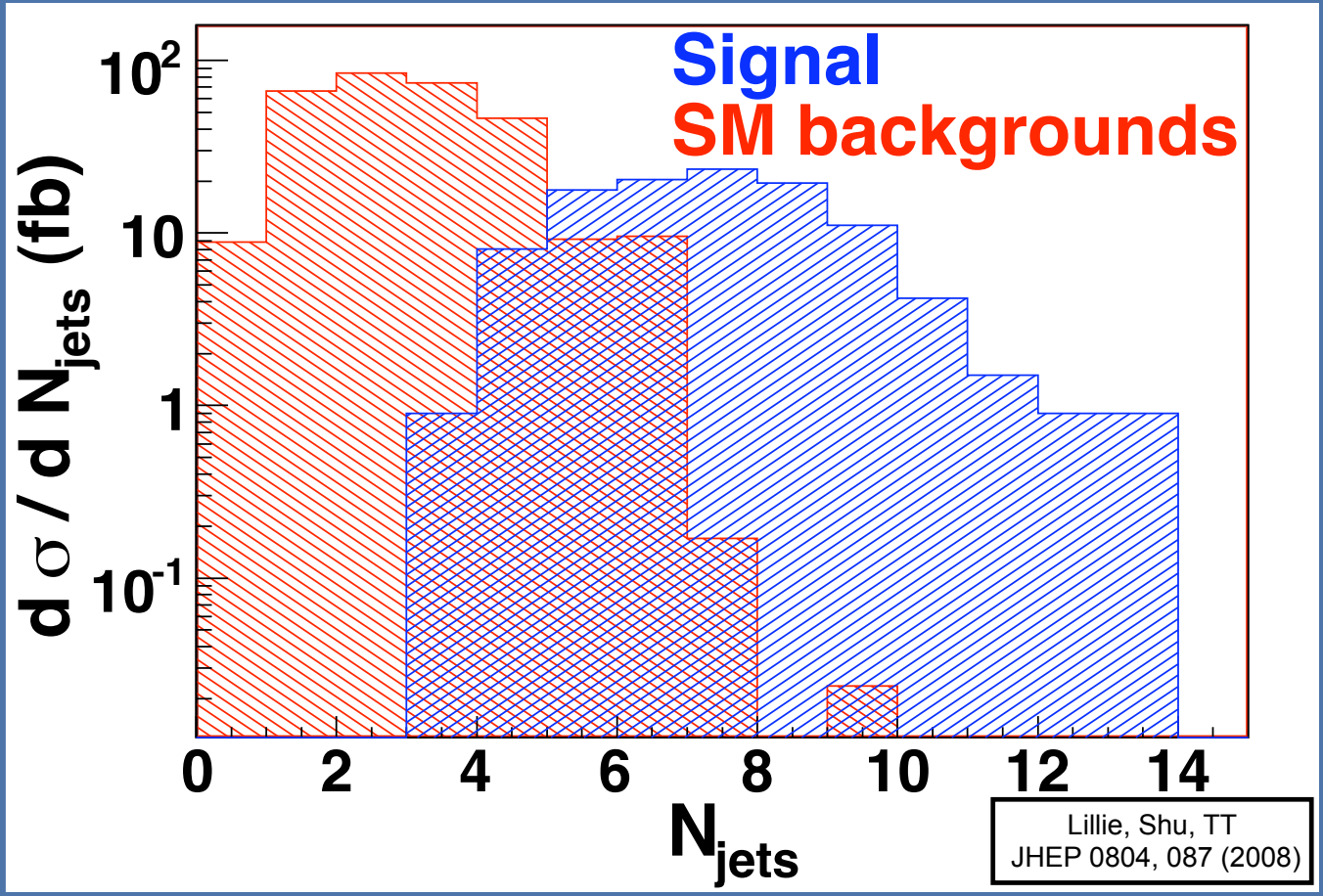
- After cuts, we are left with:
  - WW + jets: 1.1 fb (+/-: 0.8 fb / 0.3 fb)
  - WZ + jets: 1.5 fb (+/-: 1.1 fb / 0.4 fb)
  - Wbb + jet: 0.8 fb (+/-: 0.6 fb / 0.2 fb)
  - W + 3 jets: 0.6 fb (about equally + and -)
  - t t Charge mis-ID: 3.16 fb (Well simulated?!?)
- The signal (for M ~ 1 TeV, g ~ 2 π) is about 112 fb.

(Efficiency of about 3% - mostly from the W BRs)

Signal

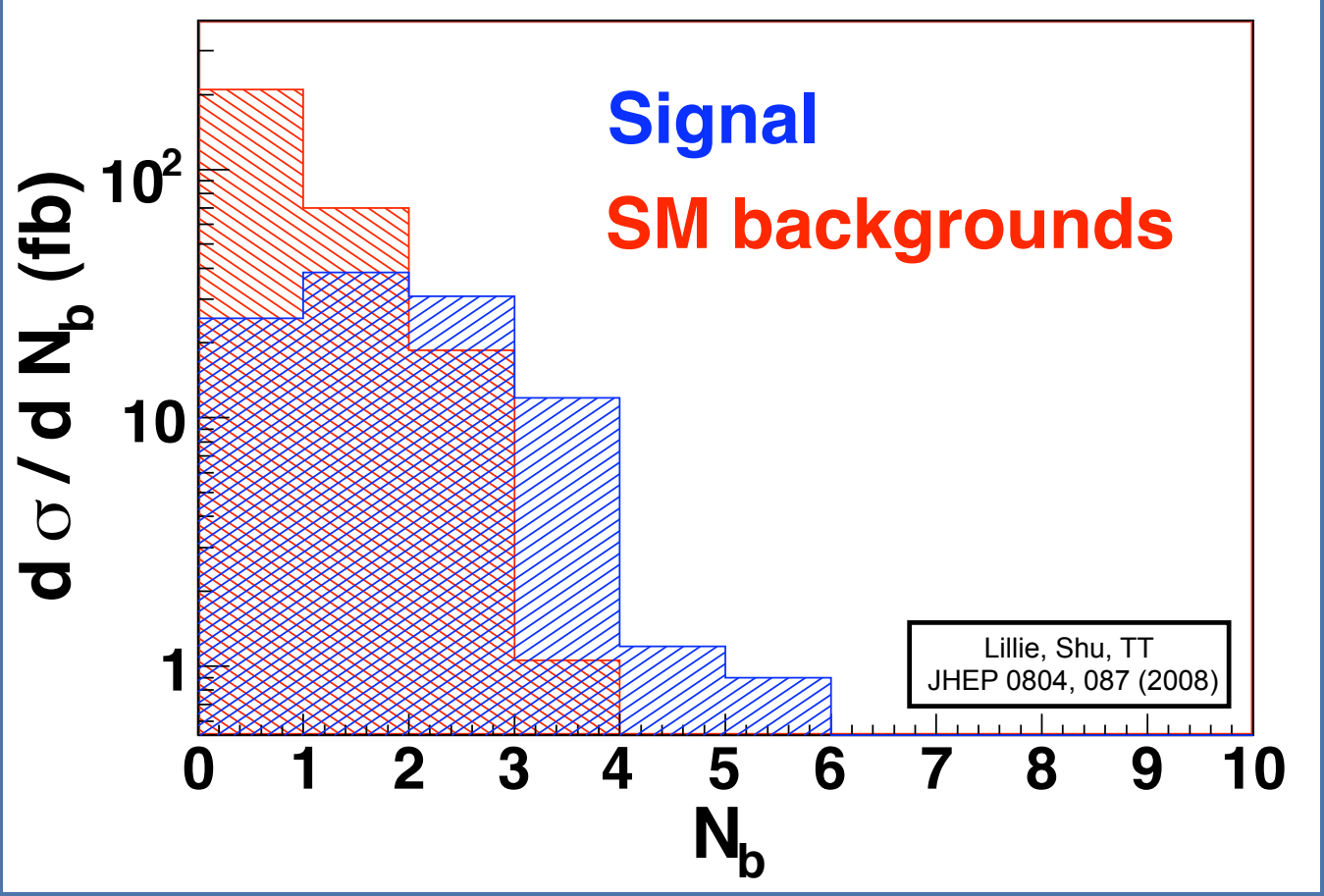
- At this point we would ideally start reconstructing tops and Ws.
  - But the combinatorics seem to be flooding us.
- So I'll settle for a few observations that the signal looks more 4-top-like than not:
  - Four tops produces equal ++ and -- lepton pairs in our signal sample. Electroweak production of charged states will not.
  - There are b-tagged jets from the top decays.
  - In general, there is a lot of jet activity.
- Jet substructure variables could be very helpful here too...

Number of Jets

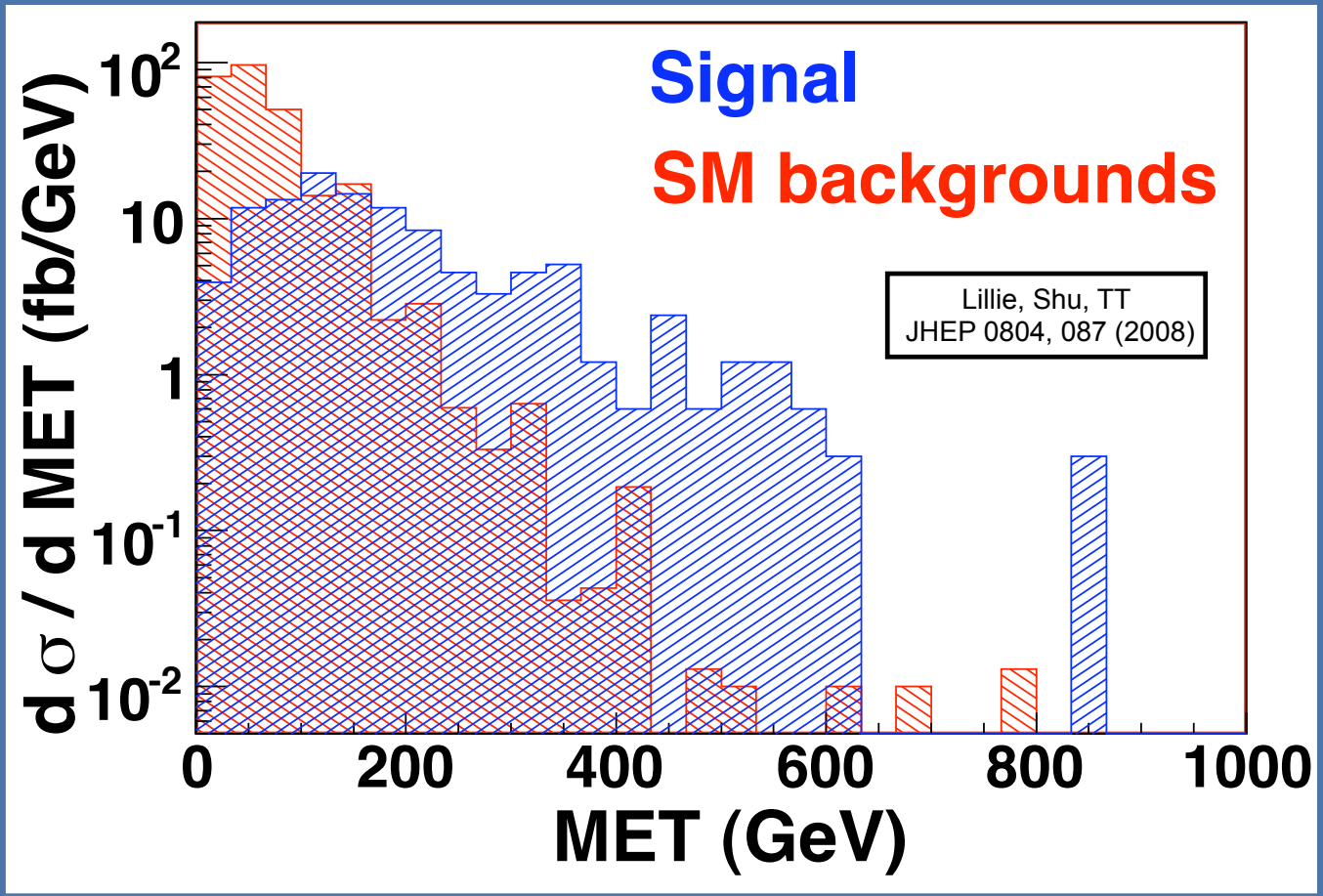


Our tops aren't tremendously boosted.

Number of b-tags

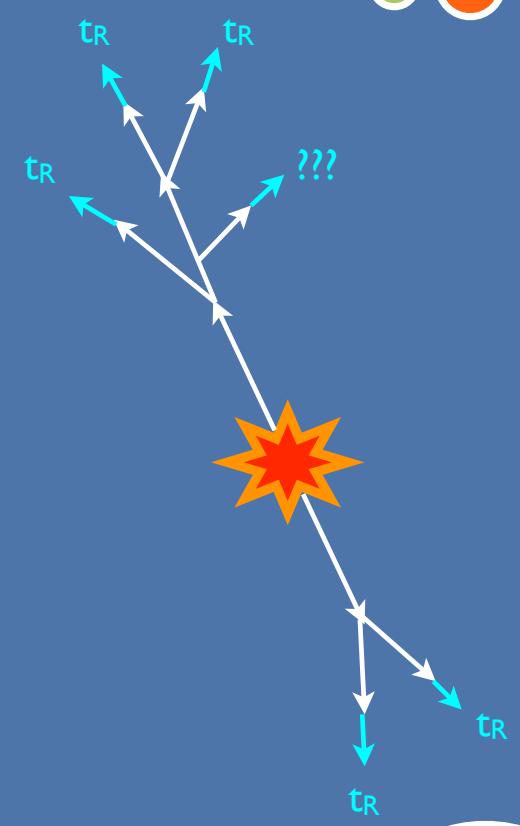


Missing ET


Signal
SM backgrounds
Lillie, Shu, TT
JHEP 0804, 087 (2008)
d σ / d MET (fb/GeV)
10^2
10
1
10^-1
10^-2
0
200
400
600
800
1000
MET (GeV)

Seeing Constituents?!

- With a low compositeness scale, we might even be able to see the 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 a lot of fun to try!



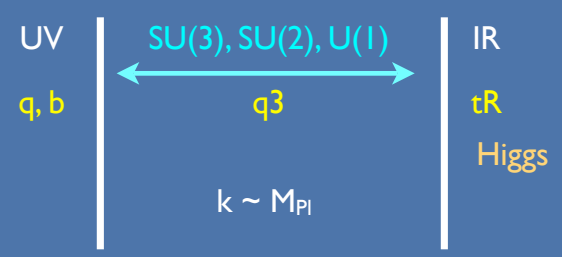
Conclusions

- The top quark is the newest component of the Standard Model. It is important to understand it as well as possible, and our hazy current understanding could lead to surprises!
- Top observables have become routine at the Tevatron but can be challenging at the LHC. There's a lot of room to improve our techniques to detect it in unusual or difficult circumstances.
- Composite models are hard to quantify, but easily lead to new signatures! It's fun to explore them!

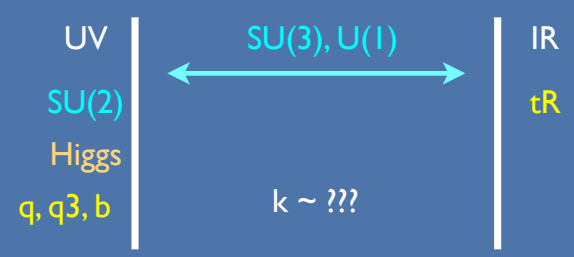
Bonus Material

Resonances

- To go past the operator description and think about resonances, we need to make some assumptions about the underlying theory. So things become necessarily more model-dependent.
- The Randall-Sundrum models with the SM in the bulk are a good place to start.
- RS models are highly constrained by precision EW observables, but the structure that is constrained is mostly related to the RS solution to the hierarchy problem. We can imagine constructions like:

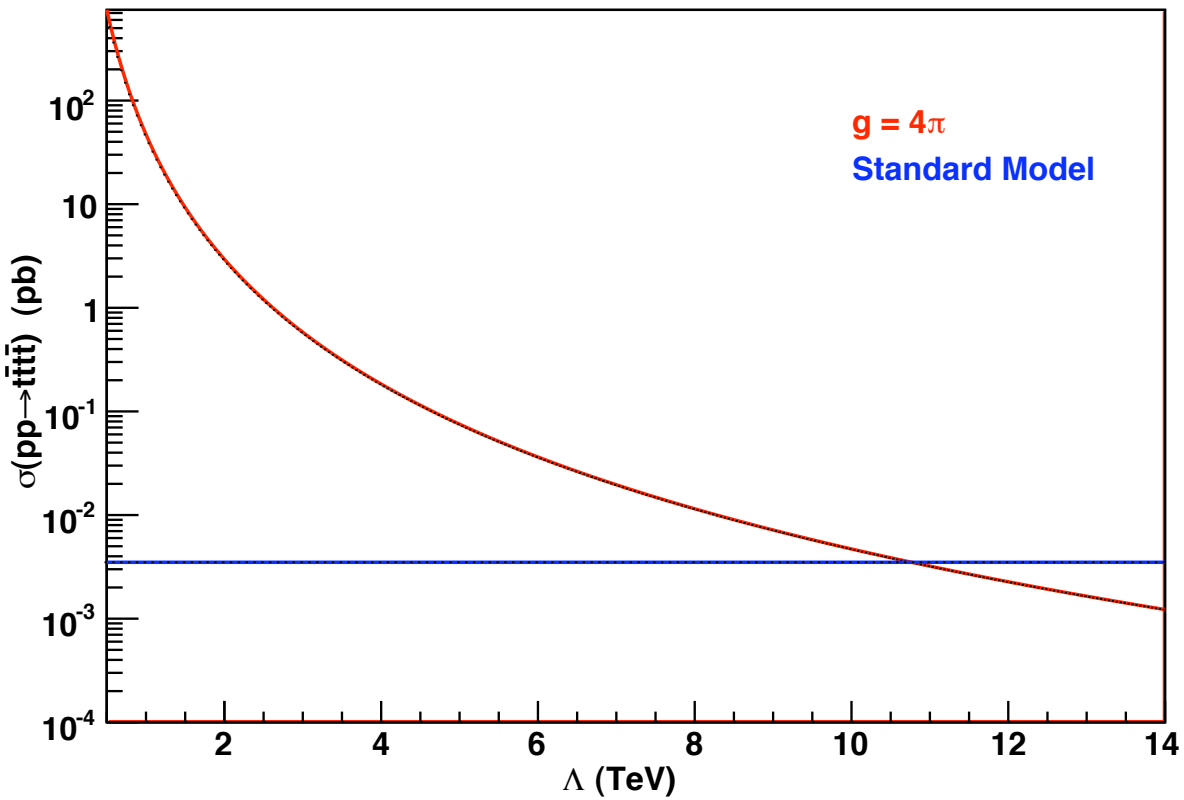
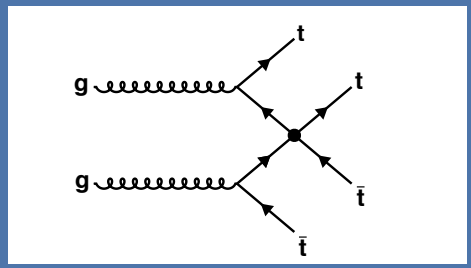


"Standard RS"



"Composite top RS"

Four tops: Operator Language



We can also describe four top production in an operator language at the LHC.