Top Compositeness at the Tevatron and LHC

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with Ben Lillie & Tim Tait,
arXiv:0712.3057

Outline

- Some general features of compositeness
  - Top compositeness : the final frontier!
- Current constraints.
  - Top pair production at the Tevatron
- LHC predictions.
  - Four top signals at the LHC.

Can we see Compositeness at the LHC?

The quick answer is...

Yes.

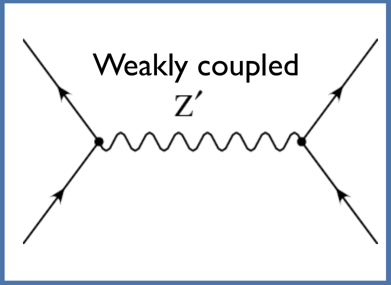
We can parameterize the low energy effects of compositeness through higher dimensional operators, and LHC will probe (some) operators up to scales of order 10's of TeV.

- Cross section
- Angular distribution of high Pt events.

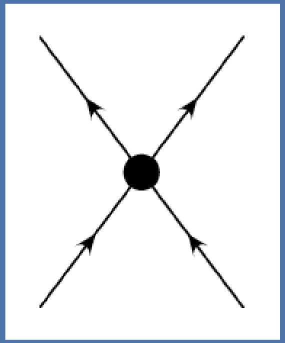
Eichten, Lane, Peskin PRL50, 811 (1983)

However, those

Higher dimensional operators could be induced by any new physics beyond the SM at the high scale, including weakly coupled theory.

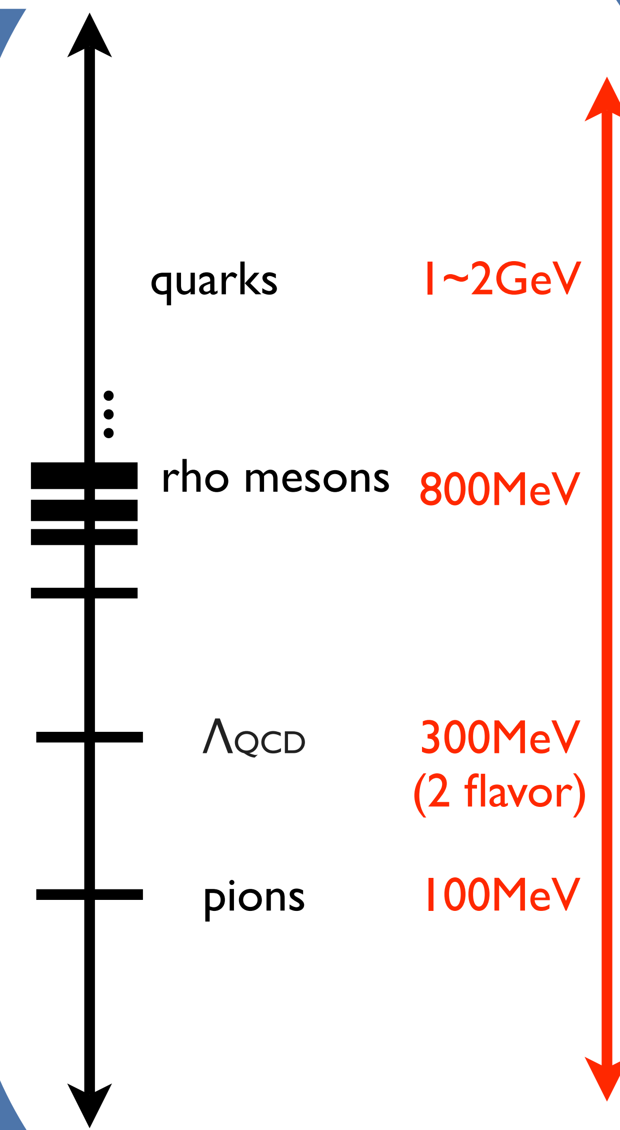


It would be better to see some phenomena which we could only associate them with compositeness and not other types of new physics.



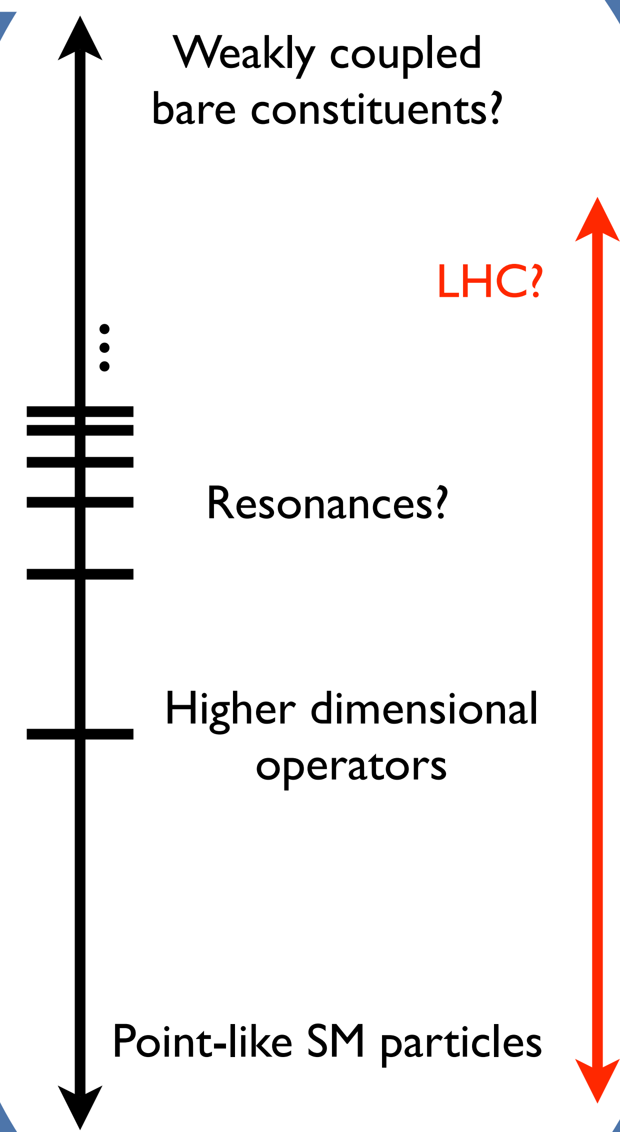
Looking back at the QCD?

- At the low energy, we see compsite light degree of freedom with their mass protected symmetry.
  - Pions (composite PNGB), mass protected by the flavor symmetry.
- At the intermediate scale, we see layers of the higher resonances with their mass associated with the comfinement scale(Λ_{QCD}).
  - rho mesons
- At sufficeint high energy scale above Λ_{QCD}, we see the constitute
  - quarks!



Compositeness at the LHC?

- At the low energy, we see SM fields with their mass protected by the electroweak gauge symmetry.
- At the intermediate scale, we see layers of the higher resonances with their mass associated with the composite scale.
  - discussed in some models beyond SM like techicolor, deconstructed moose and warped extra dimenison models in the past.
- At sufficeint high energy scale, can we see the constitutes (some people call them "preon")?



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: “Can we see something beyond the contact interactons to distinguish compositeness at the LHC?”

Constraints

- We can roughly answer the question by asking whether or not the contact interactions are valid.

$$\frac{q^2}{\Lambda^2}[\bar{q}\gamma^\mu q][\bar{q}\gamma^\mu q]$$

- Any sector for which $\Lambda >> E_{LHC,}$ it will be very difficult for the LHC to resolve the origin of compositeness, especially at the level of constituents.
- A sector for which $\Lambda > E_{LHC}$ will potentially be visible.

Different Constraints

- Leptons.
- Light quarks.
- Higgs.
- Heavy quarks.

$$\Lambda >> E_{LHC}$$

Top right?

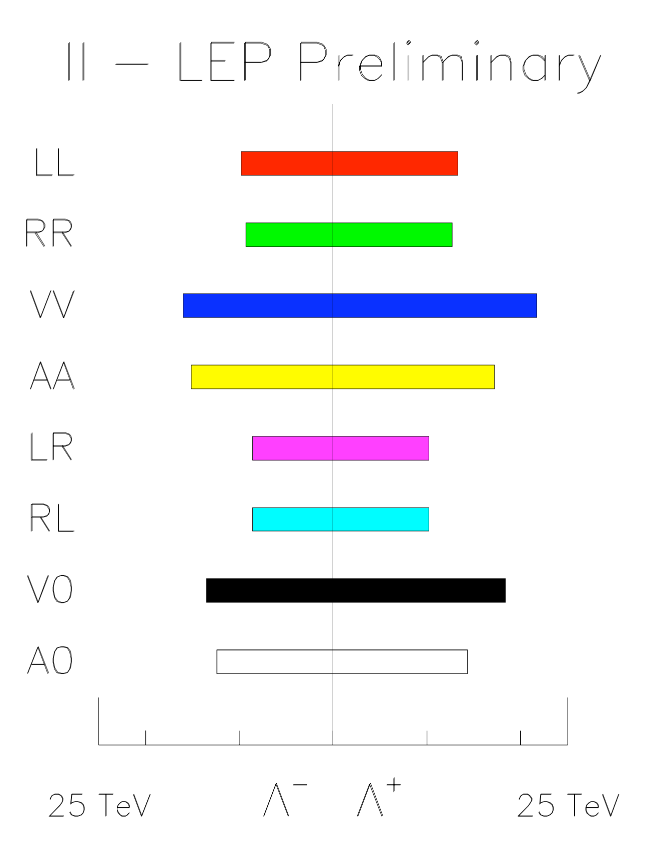
$$\Lambda \; ?$$

Leptons at LEP-II

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

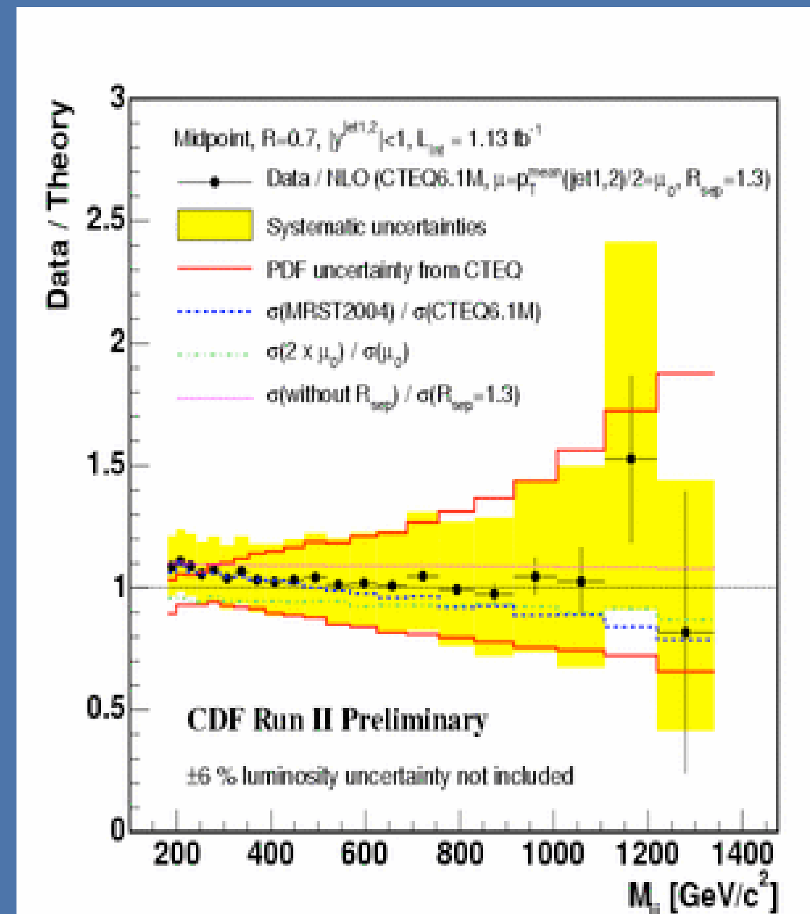
$$\frac{4\pi}{(1+\delta)\Lambda^2} \sum_{i,j=R,L} \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

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



Light Quarks at Tevatron

- Operators involving four light quarks can contribute to dijet production.
- Neither CDF nor D0 have published limits on contact interactions, though one can guess 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

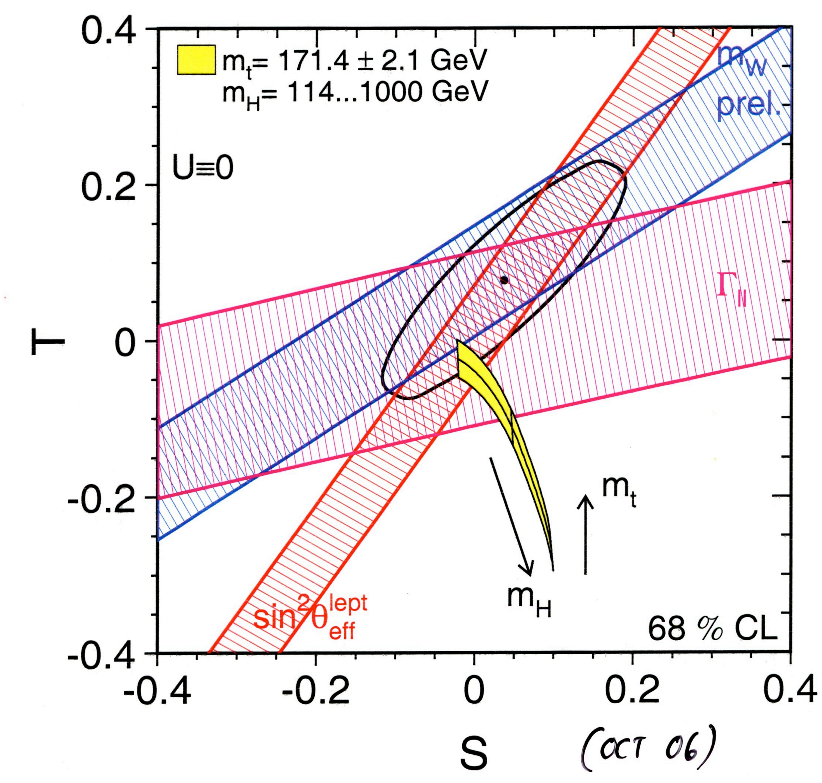
- Precision EW measurements limit Higgs operators.
  - Custodial isospin violating (T-parameter)

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

  - Custodial isospin preserving (S-parameter)

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

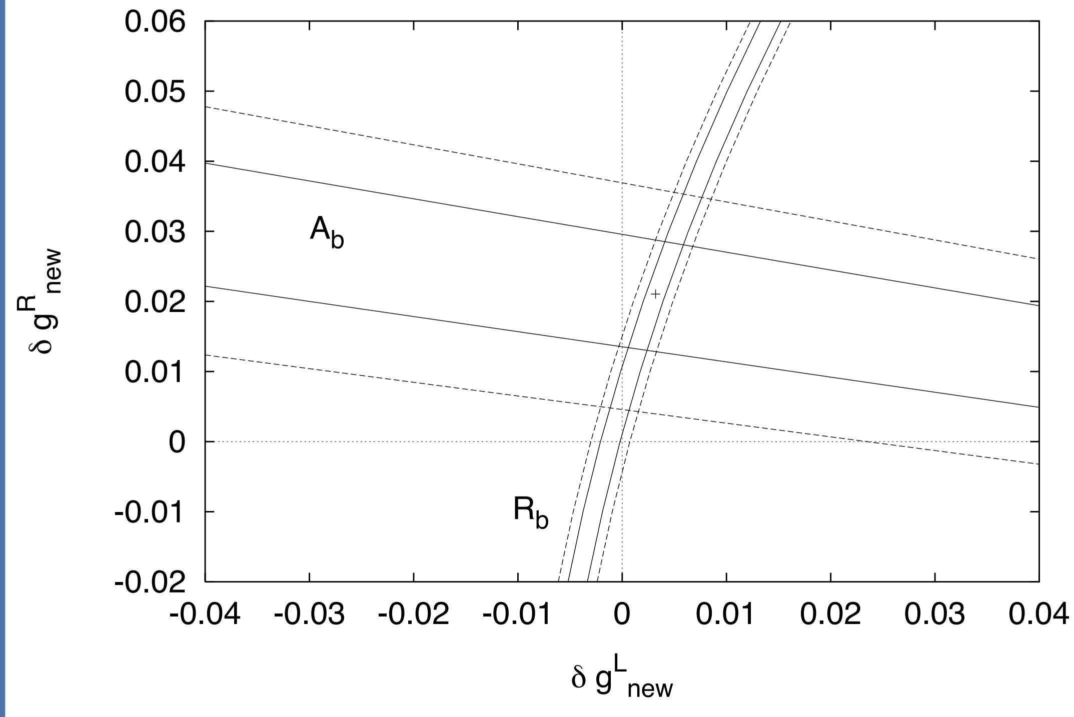
(S,T)=(0,0) at m_t=175, m_h=150



LEP EWWG

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.



Haber, Logan PRD62, 015011 (2000)

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

Composite t_R

- A composite massless fermion must come from a different strongly coupled theory than QCD as suggested by t'Hooft's anomaly matching.
- However, t'Hooft's anomaly matching is only a nessessary condition.
- We could certainly build supersymmetric theories where we have enough control over the moduli to result a unbroken flavor symmetry to protect the light super-multiplet. ("s-confinement"). The SUSY isn't buying you much beyond control over the low energy effective theory (and maybe a solution to the hierarchy problem).
  - See SUSY preon models to explain A_b^{FB} anomaly after 1995.

M. Strassler PLB 376, 119 (1996) A. Nelson, M. Strassler PRD 56, 4226 (1997)

- There are very limited examples of composite massless fermion in non-SUSY theory, and it is not a systematic way for a large class of theory.

H. Georgi NPB 266, 274 (1986)

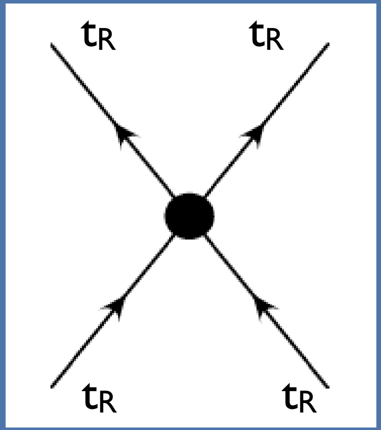
Composite t_R

- Instead, we are looking at the general coarse-grained features of t_R compositeness that affect collider signals.
- The leading operators are four right-handed tops based on NDA.

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

  - Other operators that involves derivatives are suppssed.

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

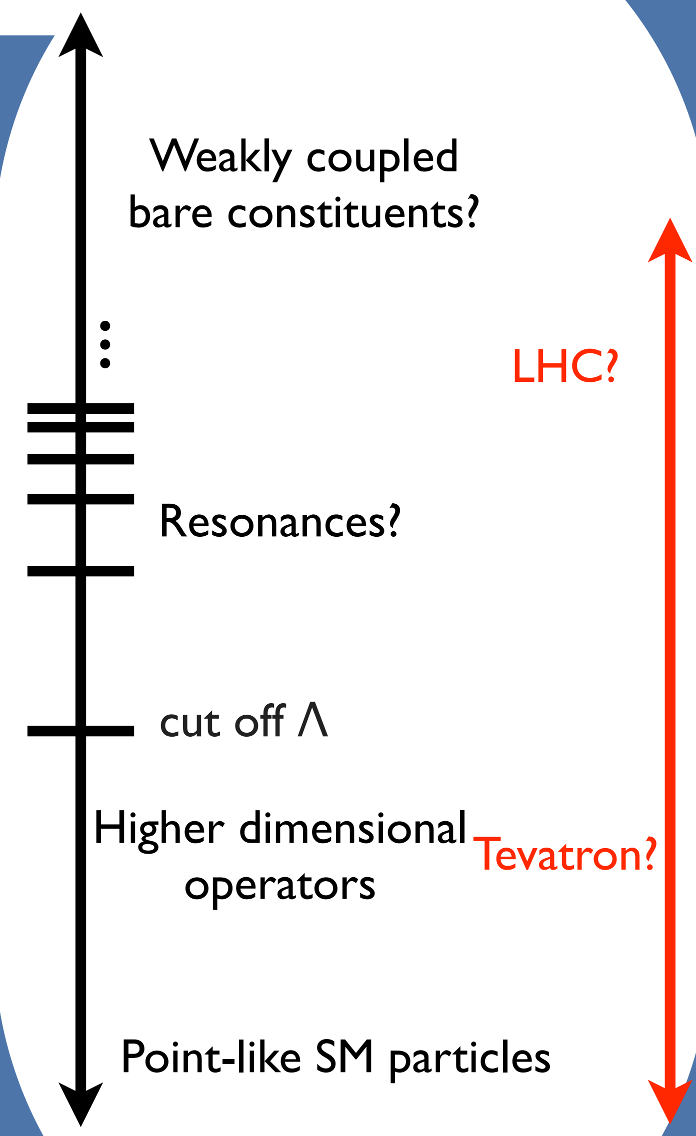


- Two interesting color structures are singlets and octets.

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

A first step!

- Let's assume at the Tevatron, the new physics involoves t_R compositeness is described by the higher dimension operators.
- We may observe the first layer of the higher resonances at the LHC.
  - We choose the vector resonance, as it is the one that naturally reduces to $4t_R$ operators at the low energy.
- It is possible to see the bare constituents, depending on the underlying dynamics (When will the underlying gauge coupling run into the weakly coupled region), and we will left it for future study.



Constrains

- Just after the discovery of top quark, there is a systematic study of all EW precision observables and flavor physics based on effective operators shows that the overall bound is

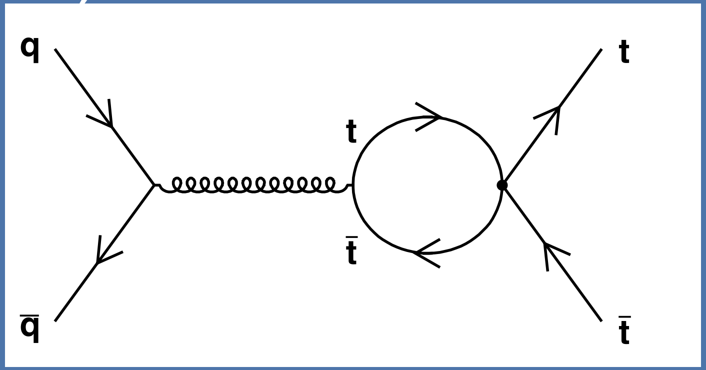
$$\Lambda > 1 \sim 2\ m_t$$

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

- The best bound comes from top pair production at the Tevatron.

Tevatron Bounds

- We compute the one loop graph (interfered with the SM graph) and keep the divergent (log-enhanced) contribution to qq --> tt.



- They corresponds to dimension six operator which could be estimated from NDA as

$$\frac{ig_s}{\Lambda^2}[\bar{t}_R D^\mu \gamma^\nu T^a t_R]G^a_{\mu\nu}$$

Top Pairs

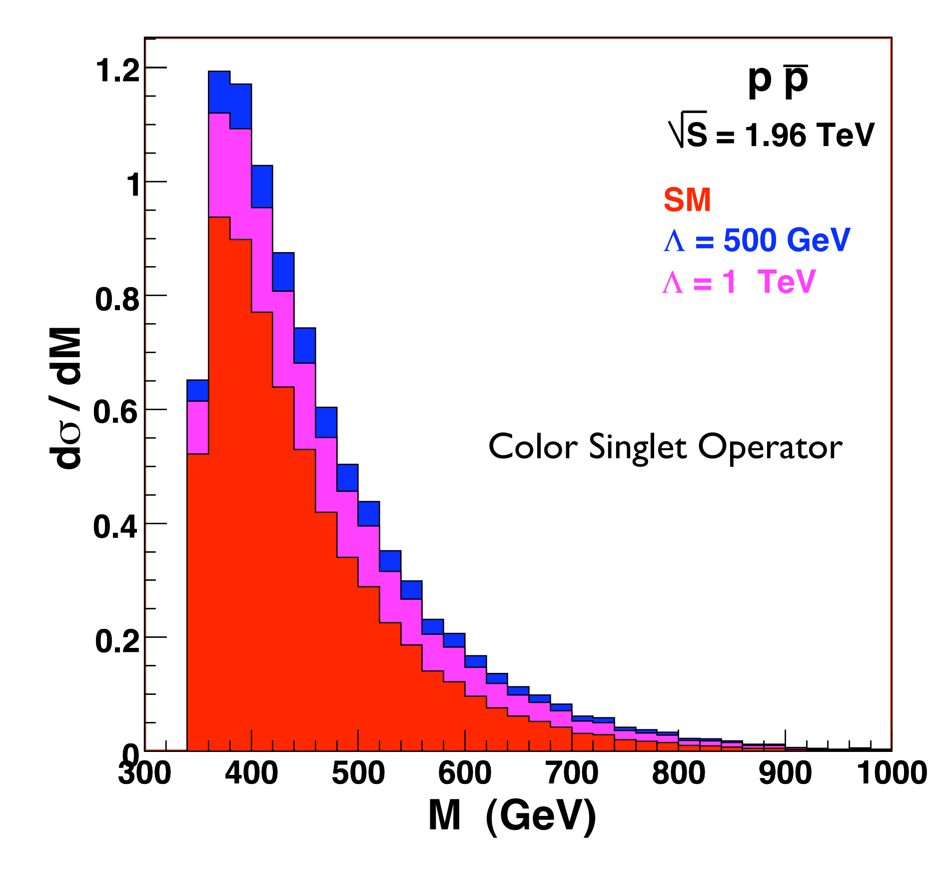
- From the underlying compositeness point of view, this graph looks like QCD production of tops, which re-scatter under the new strong dynamics.
- We neglect the gluon fusion contribution, which is about 15% or so at the Tevatron.
- The log-enhanced terms look like the SM cross section times a piece proportional to s / Λ^2:

$$\hat{\sigma}_{SM}(q\bar{q} \to t\bar{t}) \times (1 + c\frac{g^2}{(4\pi)^2}\frac{s}{\Lambda^2}\log(\frac{\Lambda^2}{m_t^2}))$$

c = +4/3 (color singlet)   c = +4/9 (color octet)

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 (c>0).
- 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.

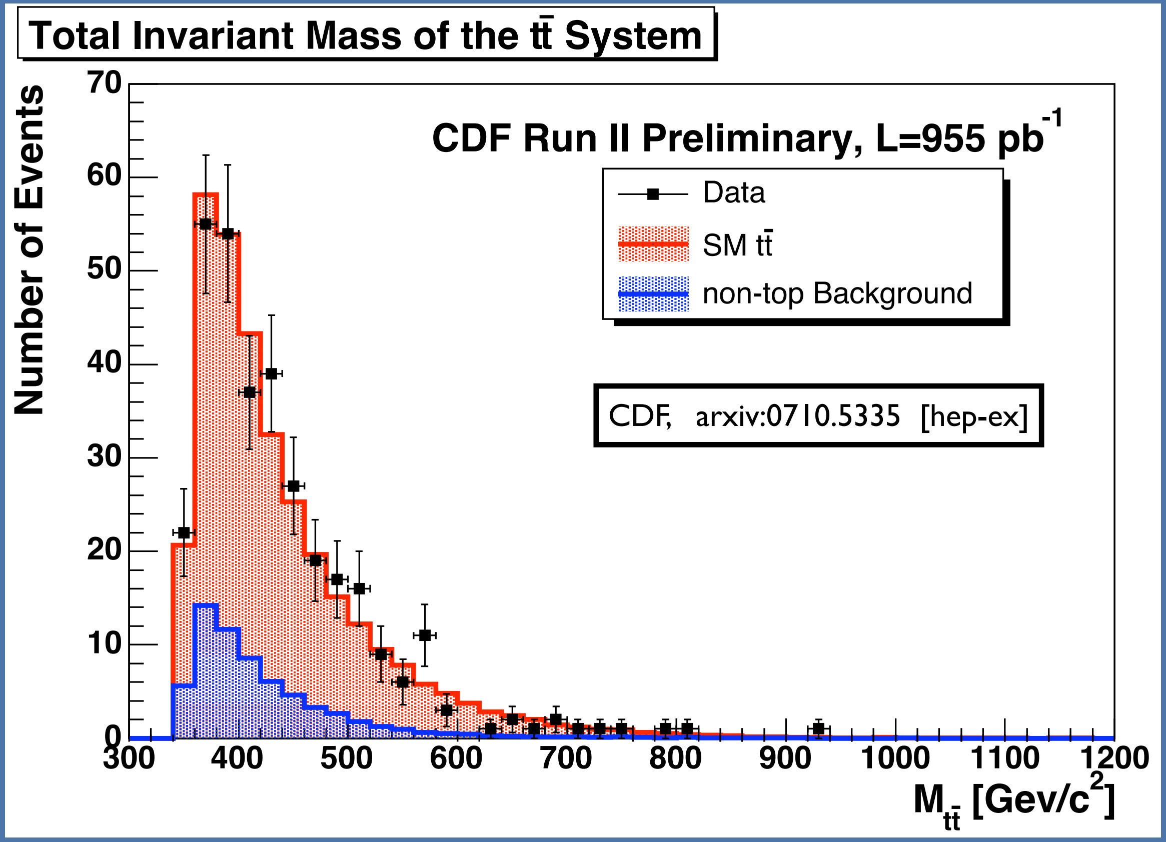


Alwall et al, JHEP 0709, 028 (2007)

$M_{t\bar{t}}$

http://www-cdf.fnal.gov/physics/new/top/2006/mass/mttb/pub_page.html

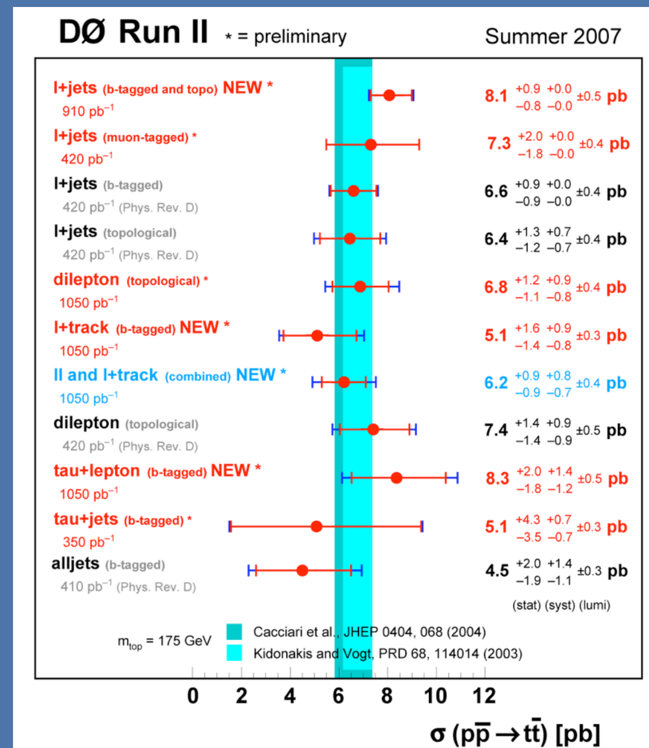
- CDF (and D0) do have results for top pairs binned in the invariant mass.
- It's not in a form that is immediately useful for a theorist, because it includes efficiencies and some non-top backgrounds.
- However, clearly there is good agreement between the theory expectation and the data.

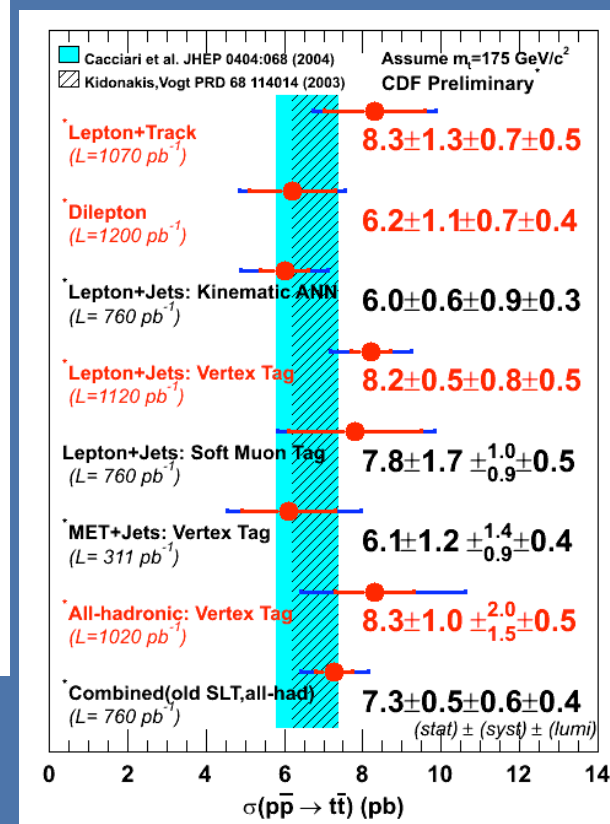


CDF uses this data to put a bound on narrow resonances decaying to top pairs.

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).





Bound on Λ

- The CDF measurement is:

$$\sigma_{CDF} = 7.3 \pm \underset{\text{(statistical)}}{0.5} \pm \underset{\text{(systematic)}}{0.6} \pm \underset{\text{(luminosity)}}{0.4} \text{ pb}$$

- Compare with the SM 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)

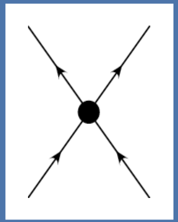
- From which we derive a bound on the size of Λ:

$$\frac{\Lambda}{g} \gtrsim 80 \text{ GeV} \qquad (\Lambda \gtrsim 1 \text{ TeV for } g \sim 4\pi)$$

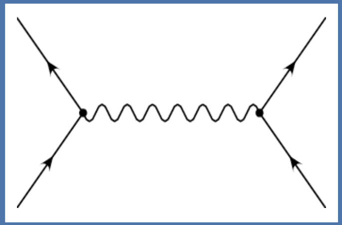
- This is small enough to use effective theory at LHC...

Mapping to Resonances

- Mapping the constraint on the operator to the properties of the vector meson is still model dependent...
  - How many resonances?
  - Its color structure.
  - How strongly coupled are they?
  - Is a single resonance good enough?
  - 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 (singlet or octet).

Resonances

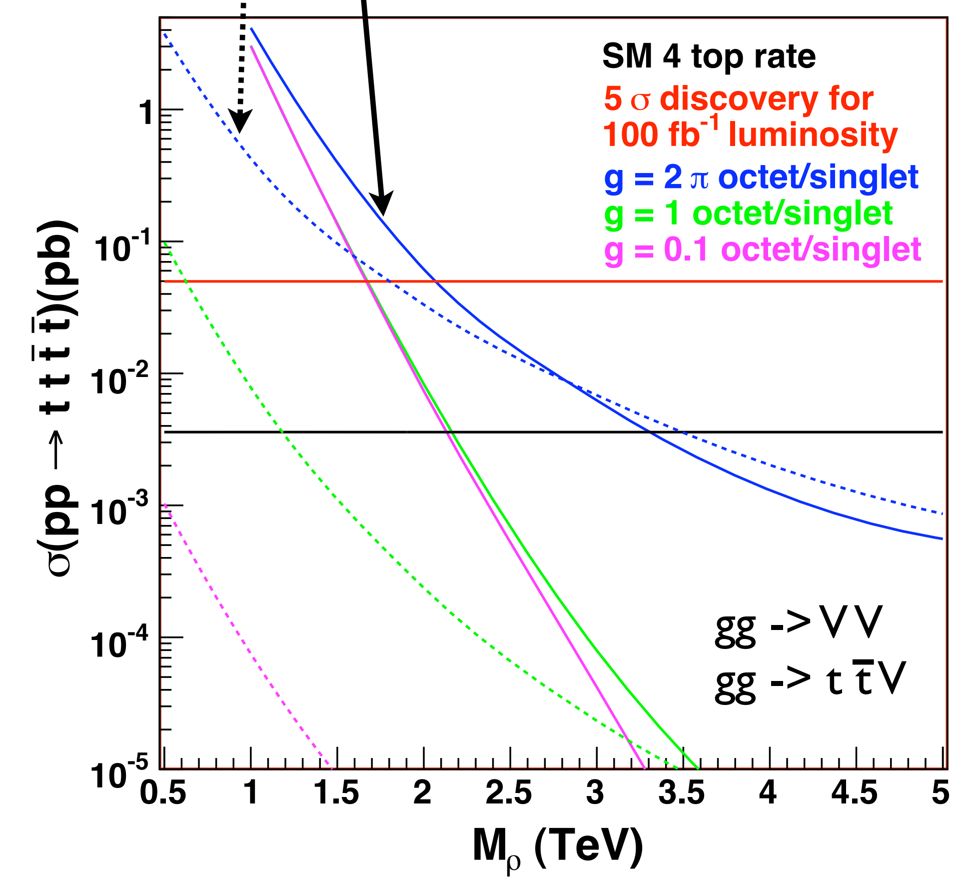
- We expect the mutiple production of the light composites will be highly enhanced. In particular, we focus on the 4 top production.
- We assume the the vector meson have the folowing properties related to the 4 top production.
  - For the color singlet vector meson, it only couples to right handed top.
  - For the color octet vector meson, it also couples to gluon through the couplings v-g-g and v-v-g-g with their strength g_s and g_s^2 respectively. (notice the coupling strength here is guarateened by the gauge invaraince of QCD)

Four Tops at the LHC

The dashed lines are singlet, while the solid lines are octet.

- As a general analysis, we varing the coupling v-tR-tR and the mass of the vector meson.
- It is important to notice that the pair production of v is a constant.
  - The vector meson are mostly pair produced by the gluon fusion for small v mass.
  - When v mass is large, it is easy to rescattering the top (produce one v) instead of pair producing v.

4 top rate amplified by 1000!!!



SM four top rate: a few fb (3.9)

Four tops?

- The question is: can we actually reconstruct four tops at the LHC?
- 4 top events typical gives a very large number of hard jets, which makes it very difficult to reconstruct the SM objects.
- A recent study concluded we can, but used a jet mass technique which is probably very sensitive to underlying event and mismeasurement.

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

  - And they typically recontruct only one of the four tops!

low reconstructing efficiency

  - It requires us to reconstruct at least 3 tops, that will significantly reduce the number of useful events.

Four top-like ?

- We went with a more conservative approach, and required two like-sign leptons (either electron or muon) together with 2 or more hard jets.
- Our strategy is that : After extracting the signal from the background (we keep the signal as much as possible), we can look at the shape of several kinematical distributions 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. fake rate 10^{-4}
  - $W^{+}W^{-}$ + 2 jets ($t\,\bar{t}$) with a charge mis-identified (main background).

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.
  - 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).

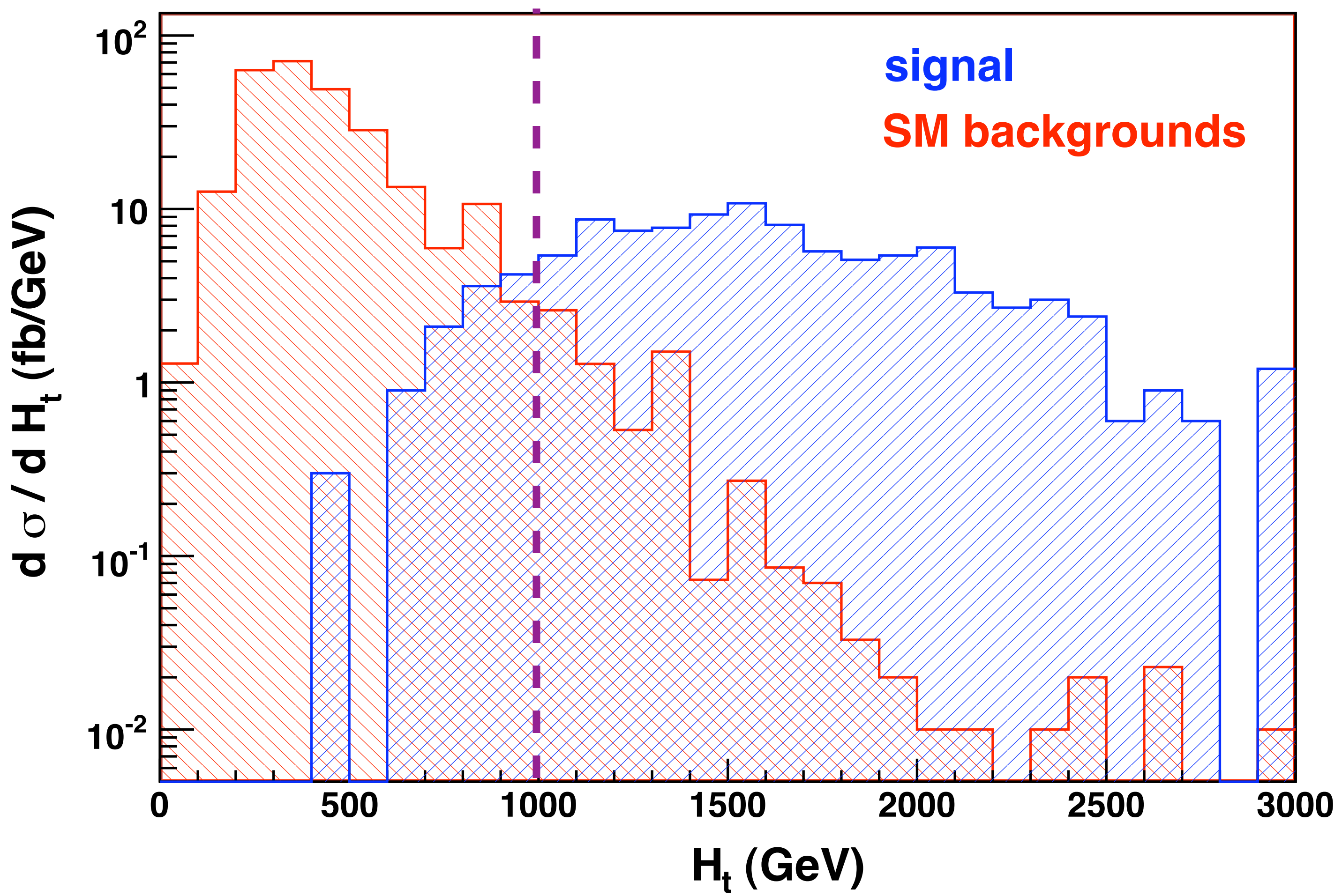
Cuts

- 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, $|y| < 2.5$.

We could ask for more hard jets, but Madgraph simulation will cost much more time

- We reject the events if one can reconstruct Z from the leptons.
- To reject the leptons from 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 > 1000 GeV.

H_t Distribution



Backgrounds

- Before cuts, we have:
  - $W^{\pm}W^{\pm}$ + 2 jets: 0.42pb (+/-: 0.29 pb / 0.13 pb)
  - $W^{\pm}Z$ + 2 jets: 10.76pb (+/-: 6.65 pb / 4.11 pb)
  - $W^{\pm}b\bar{b}$ + jet: 332pb (+/-: 196 pb / 136 pb)
  - $W^{\pm}$ + 3 jets: 0.37e4 pb (+/-: 0.217e4 pb / 0.152e4 pb)
  - $W^{+}W^{-}$ + 2 jets ($t\,\bar{t}$): 390 pb NLO 830pb
- The signal (for M ~ 1 TeV, g ~ 2 π) is about 3.6 pb.

Backgrounds

- After cuts, we are left with:
  - $W^{\pm}W^{\pm}$ + 2 jets: 1.15 fb (+/-: 0.83 fb / 0.32 fb)
  - $W^{\pm}Z$ + 2 jets: 1.53 fb (+/-: 1.12 fb / 0.41 fb)
    - The Z is decaying leptonically...we could use an invariant mass cut to reject the Z.
  - $W^{\pm}b\bar{b}$ + jet: 0.75 fb (+/-: 0.57 fb / 0.18 fb)
  - $W^{\pm}$ + 3 jets: ~ 0.61 fb (+/-: 0.32 fb / 0.29 fb)
  - $W^{+}W^{-}$ + 2 jets ($t\,\bar{t}$): 3.16 fb
- The signal (for M ~ 1 TeV, g ~ 2 π) is about 97.5 fb.

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

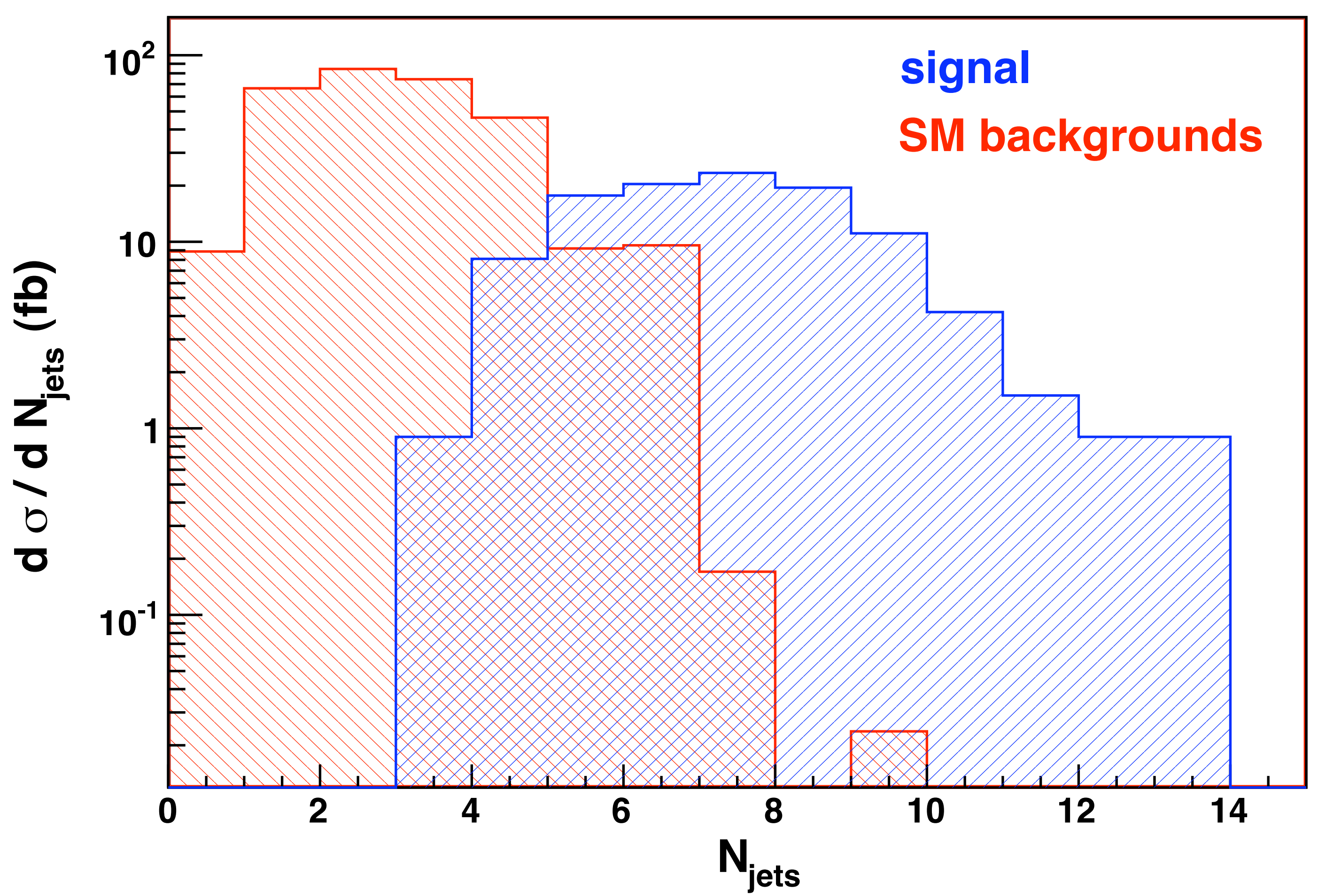
Signal

- For a 5σ discovery, the required signal (45fb) is about 10 times the SM 4 top production.

  It could be reduced if we put stronger cuts.

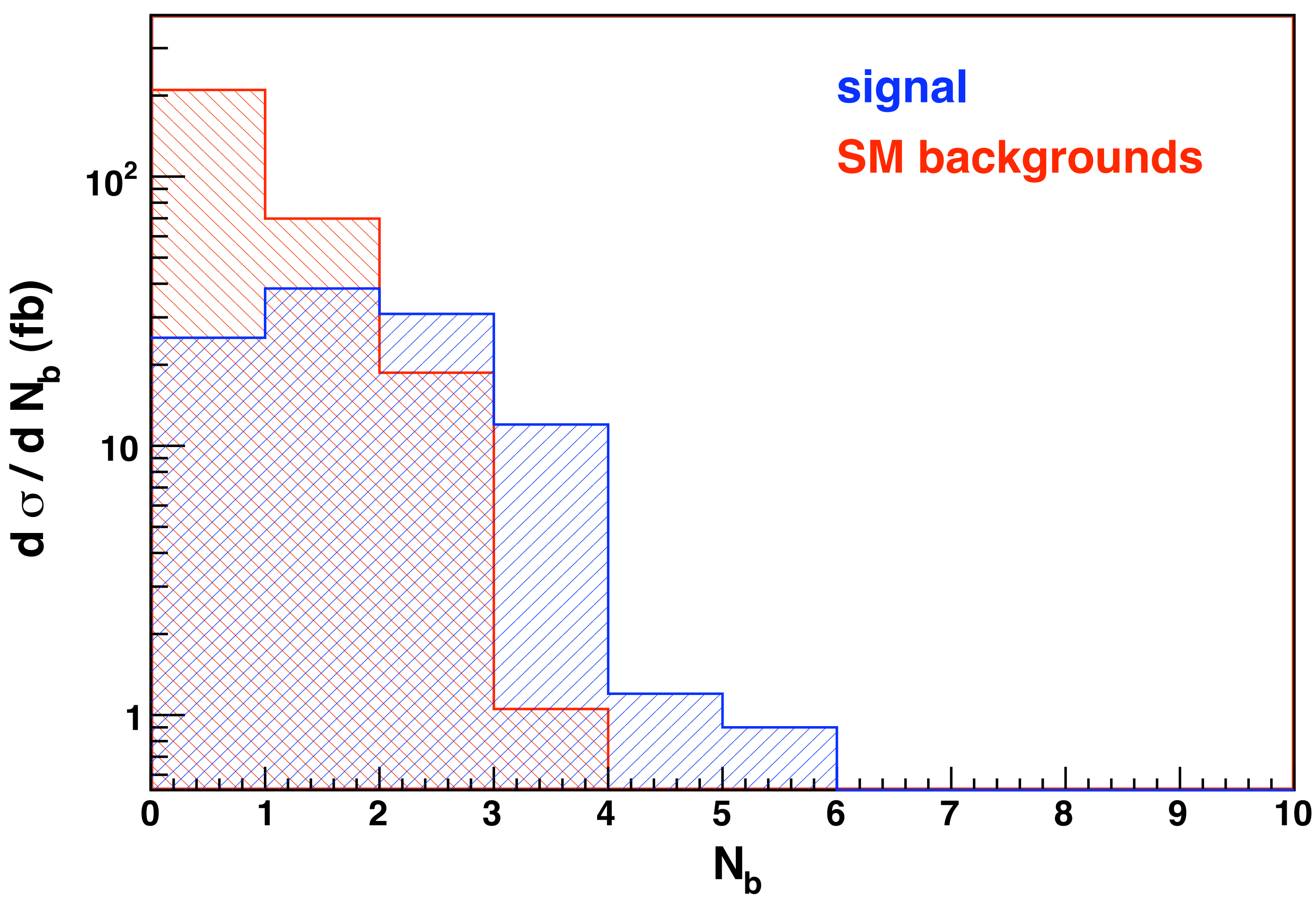
- So I'll settle for a few observations that the signal looks more 4-top-like than not:
  - Four tops produces equal ++ and -- lepton pairs in our signal sample. Electroweak production of charged states will not.
  - There are b-tagged jets from the top decays.
  - In general, there is a lot of jet activity.

Number of Jets

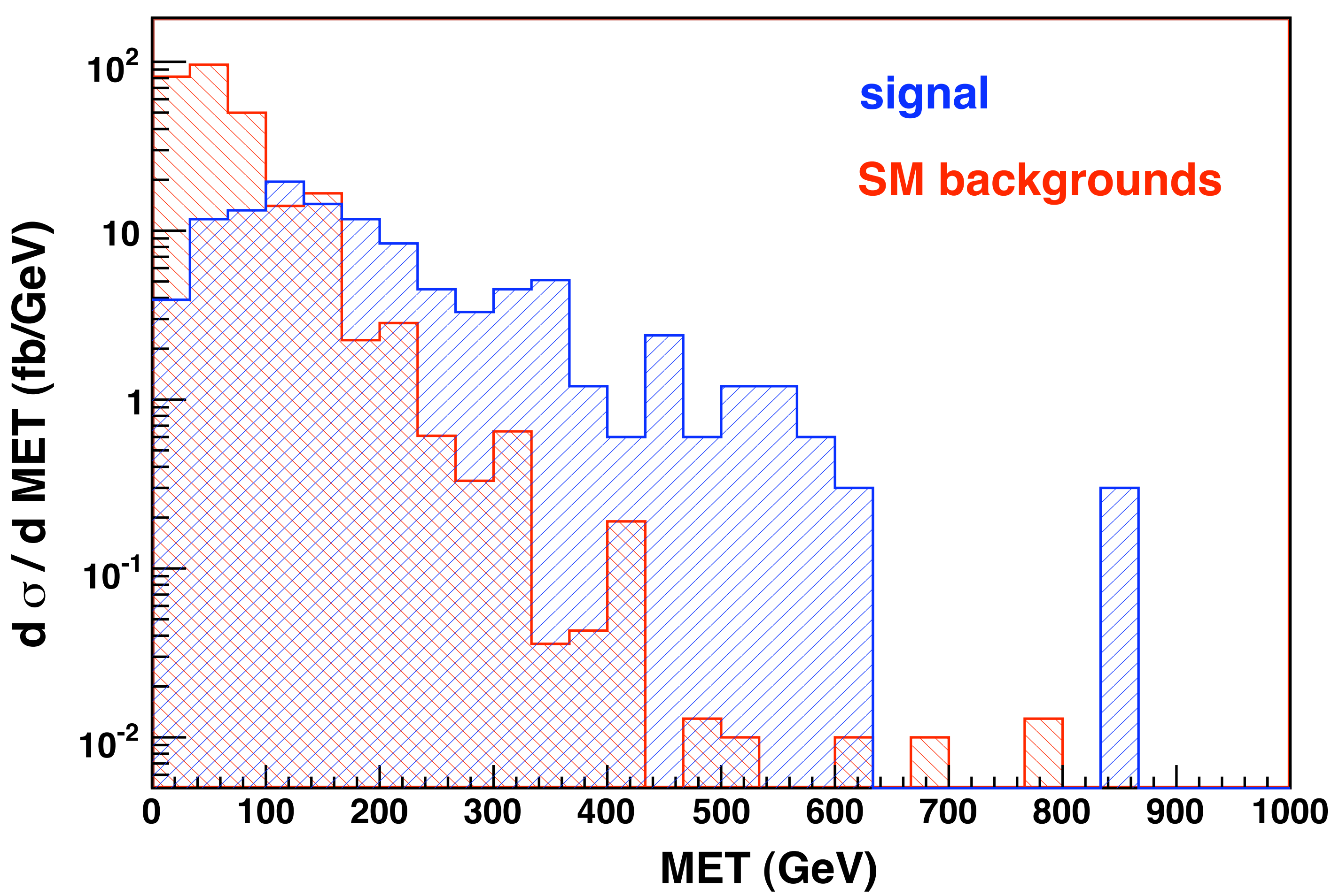


Our tops aren't tremendously boosted.

Number of b-tags



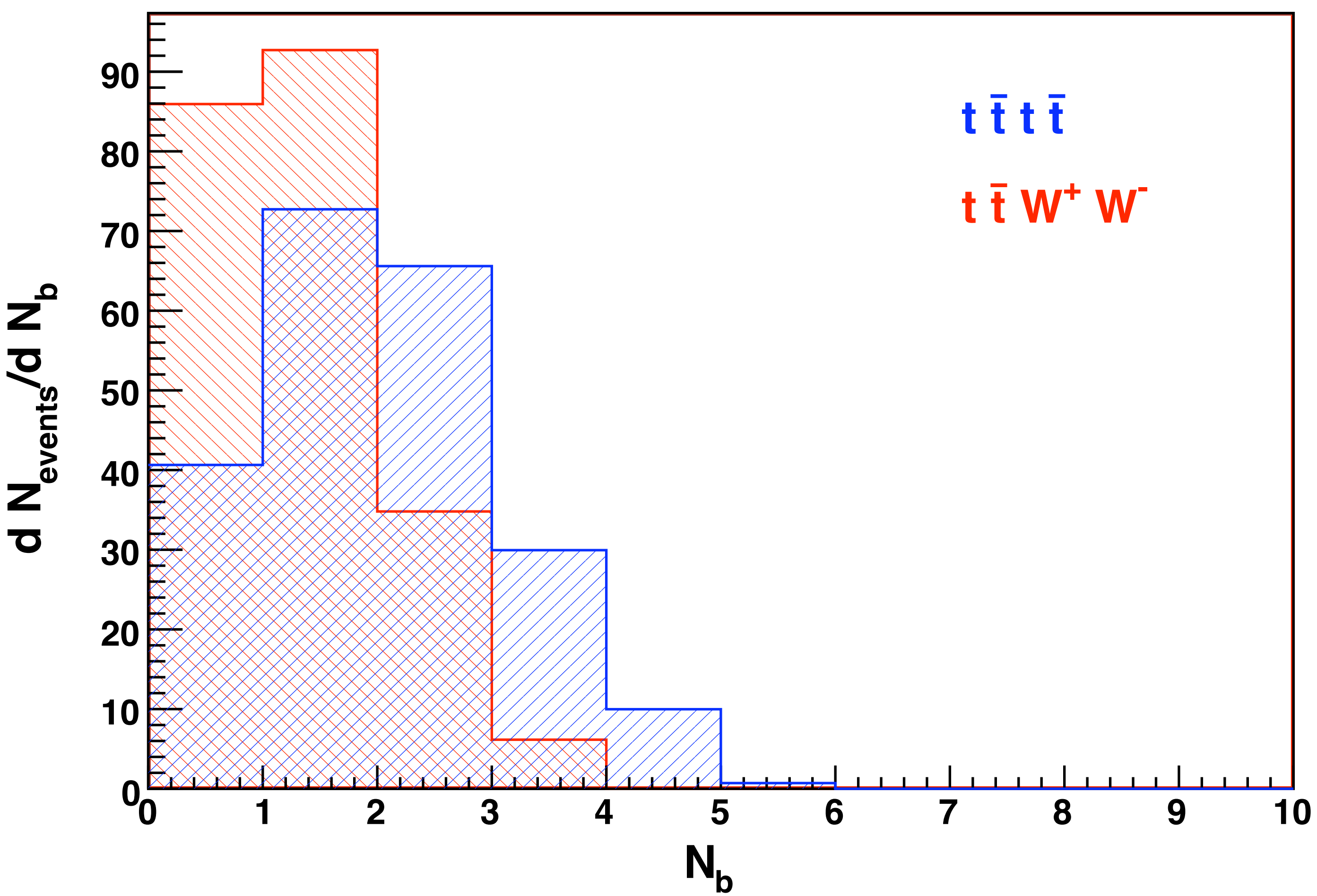
Missing Energy



Signal

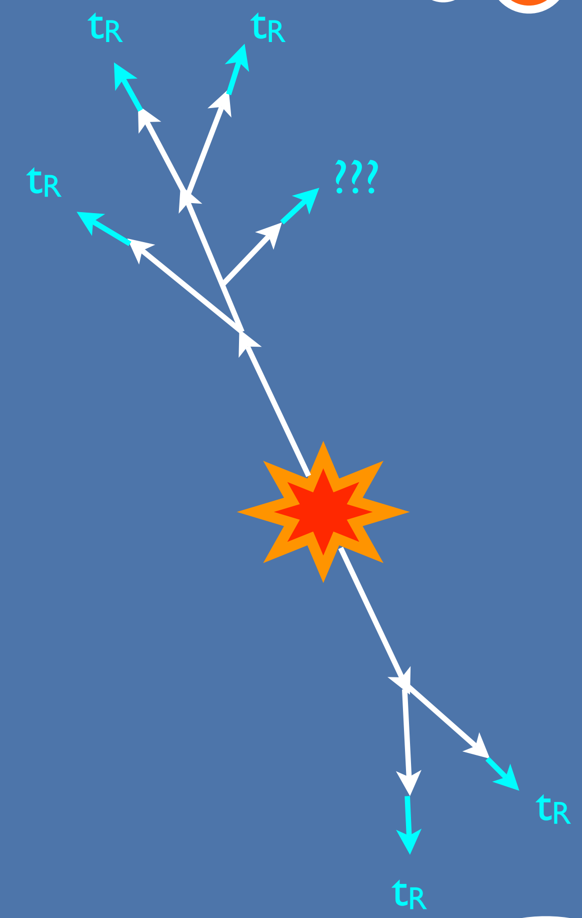
- Other models may lead to 4 top like signals with large cross section, we may still distinguish them.
  - SUSY ?
    - The glunio pair production when the branching ratio of $\tilde{g} \to \tilde{t}\bar{t} \to t\bar{t} + \tilde{\chi}^0$ is large
    - The MET distribution will tell us the difference.
  - RS with extended custodial symmetry.
    - The b' pair production when b' most decays into W and top.
    - There are fewer number of b jets there so the N_b distributions may tell us the difference.

Number of b-tags



Future Directions?

- 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?



Conclusion

- The top quark is the newest component of the Standard Model. It is important to understand it as much as possible, and our current understanding could lead to some surprises!
- Top observables have become a routine at the Tevatron but can be very challenging at the LHC. There's a lot of room to improve our techniques to detect it in unusual or difficult circumstances (collimated top) (4 top).
- Composite models are hard to quantify, but easily lead to new signatures! It's interesting to explore them!