Top Compositeness at the Tevatron and LHC

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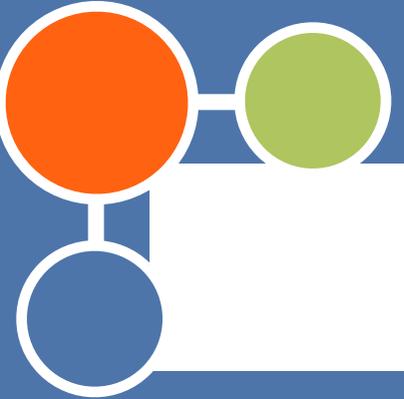
Outline

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

Eichten, Lane, Peskin PRL50, 811 (1983)

It sounds great, but...

Higher dimensional operators could be induced by any new physics beyond the SM at the high scale, including weakly coupled theory.
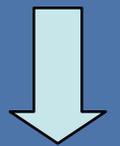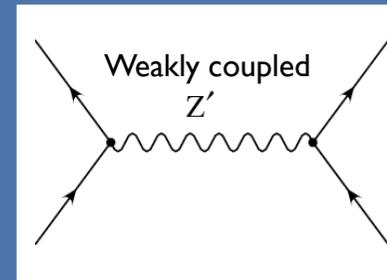
It would be better to see some phenomena which we could only associate them with compositeness and not other types of new physics.
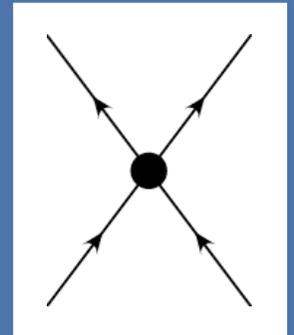
Looking back at the QCD?

● At the low energy, we see composite 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!

quarks   1~2GeV

rho mesons   800MeV

Λ_{QCD} 300MeV (2 flavor)

pions   100MeV
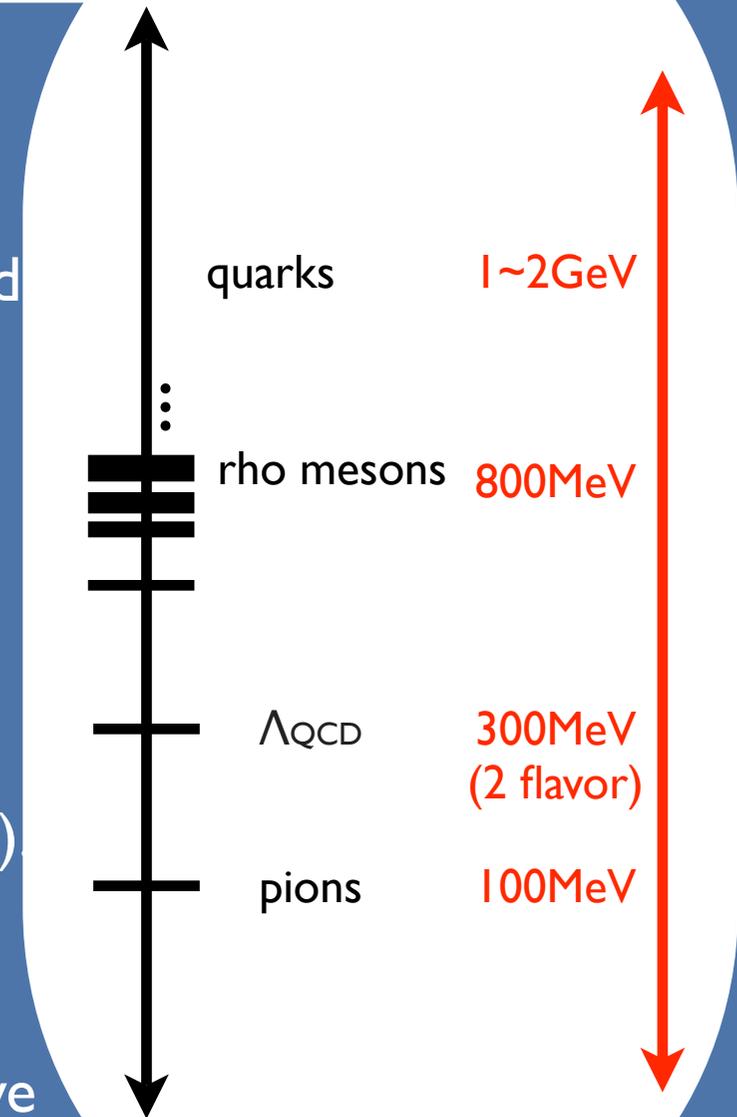
Compositeness ?

In order to resolve the origin of compositeness at LHC, we need $E_{LHC} > \Lambda$ such that effects closely connected to strong dynamics (higher resonance? constituents?) will potentially be visible.

However,

○ Leptons

○ Light quarks

○ Heavy quarks except t_R

○ Higgs

$$\Lambda > E_{LHC}$$

Leaving t_R!

A first step!

- Let's assume at the Tevatron, the new physics invoZloves t_R compositeness is described by 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, and we will left it for future study.

Weakly coupled
bare constituents?

⋮

LHC?

Resonances?

cut off Λ

Higher dimensional
operators

Tevatron?

Point-like SM particles
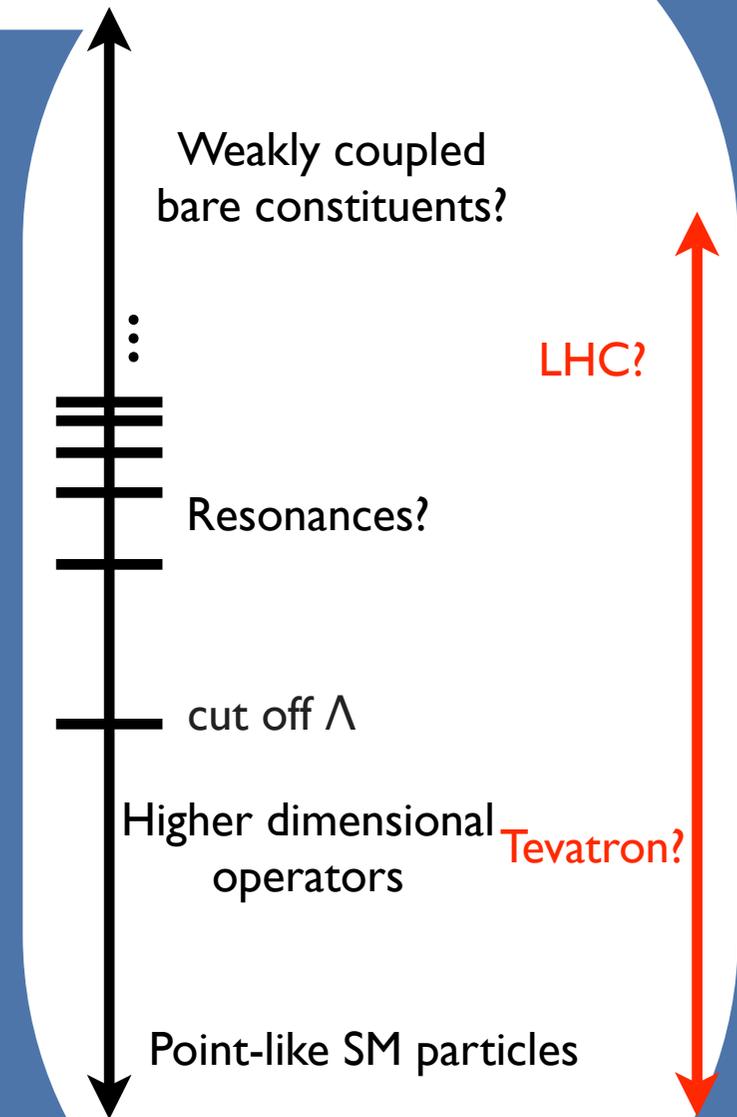
Tevatron Bounds

- The best bound comes from top pair production at the Tevatron.
- The largest operator is the interaction of four right-handed tops.
 - Other operators that involves derivatives and fundamental fields are suppressed based on NDA

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

- Two interesting color structures are singlets and octets.

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

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

t_R t_R

t_R t_R
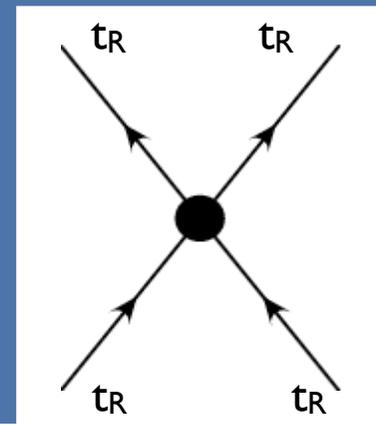
Tevatron Bounds

- We compute the one loop graph (interfered with the SM graph) and keep the divergent (log-enhanced) contribution to qq --> tt.
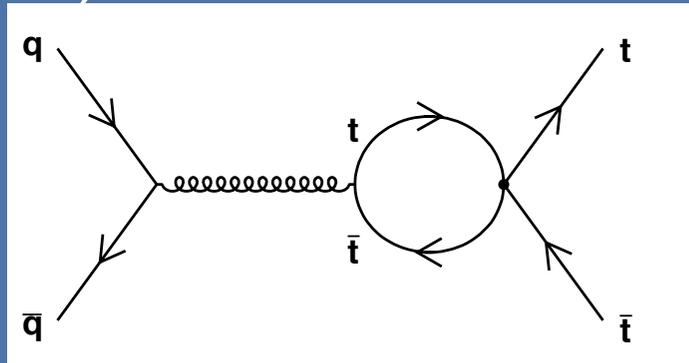
- The log-enhanced terms look like the SM cross section times a piece proportional to s / Λ²:

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

c = +4/3 (color singlet)   c = -2/9 (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).

- However, the experimental data is not in a form that is immediately useful for a theorist, because it includes efficiencies and some non-top backgrounds.

- Instead, we consider the total cross section.

$p\,\bar{p}$

$\sqrt{S} = 1.96$ TeV

SM
$\Lambda = 500$ GeV
$\Lambda = 1$ TeV

Color Singlet Operator

$d\sigma / dM$

M (GeV)
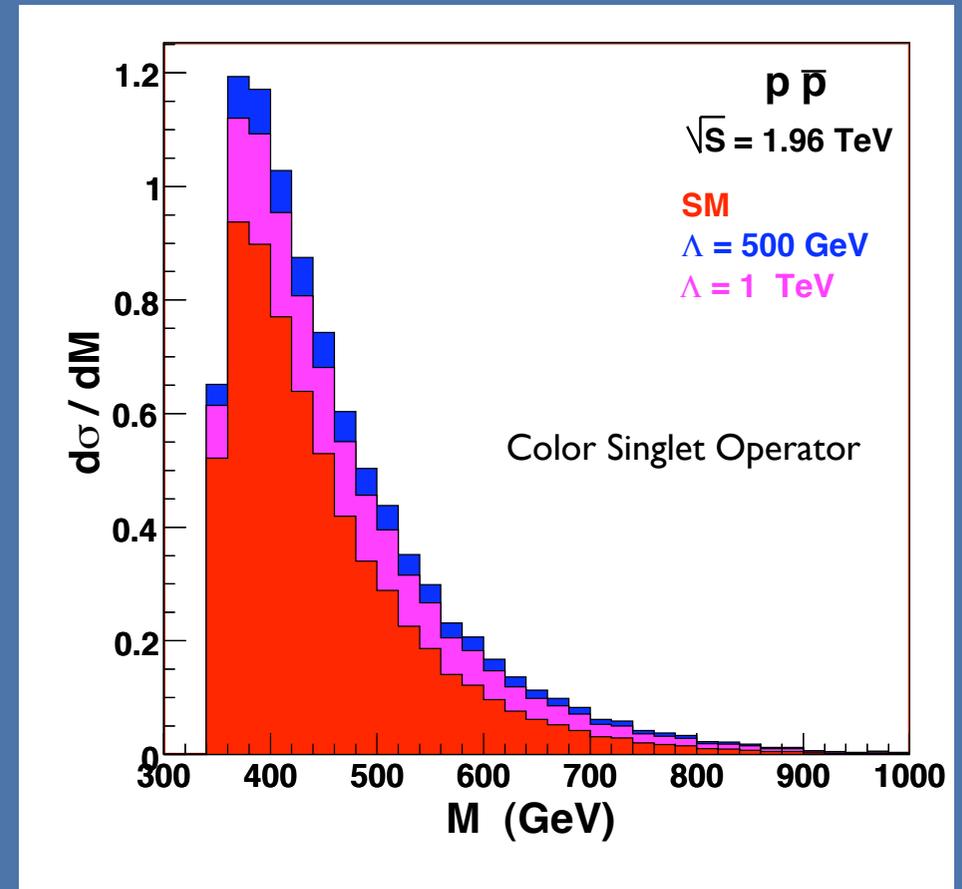
Bound on Λ

- The CDF measurement is:

$$\sigma_{CDF} = 7.3 \pm 0.5 \pm 0.6 \pm 0.4 \ \text{pb}$$

(statistical) (systematic) (luminosity)

- 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...
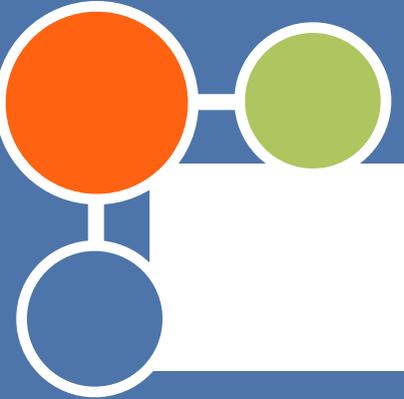
At the LHC,

- We expect the mutiple production of the light composites will be highly enhanced. In particular, we focus on the 4 top production.

- We assume that the the vector meson (singlet or octet) has the following properties related to the 4 top production.

  - Only one single vector boson with moderately strong couplings

  - 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 invairance of QCD)

Four Tops Production

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

- As a general analysis, we varing the coupling v-t_R-t_R 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 rescatter the top (produce one v) instead of pair producing v.

4 top rate amplified by 1000!!!

SM 4 top rate
5 σ discovery for 100 fb⁻¹ luminosity
g = 2 π octet/singlet
g = 1 octet/singlet
g = 0.1 octet/singlet

gg -> V V
gg -> t t̄ V

σ(pp → t t̄ t t̄)(pb)

M$_\rho$ (TeV)
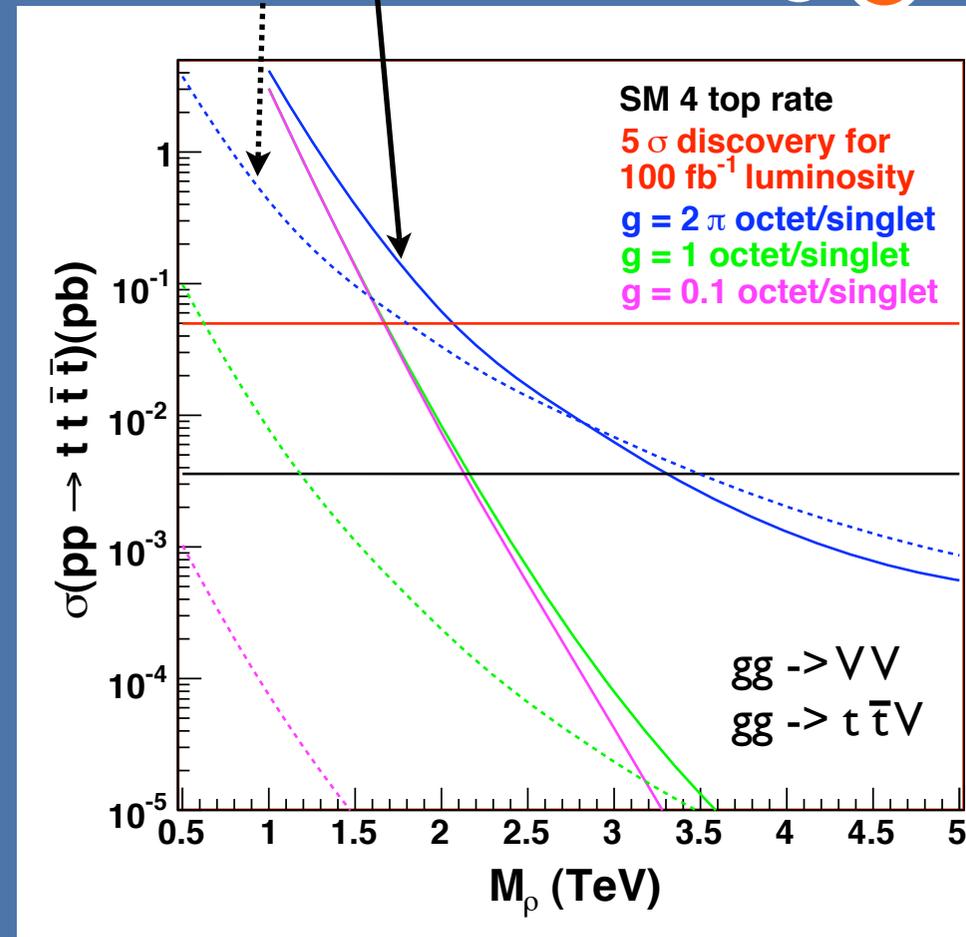
SM four top rate: a few fb (3.9)

Four tops at the LHC?

- The question is: can we actually reconstruct four tops at the LHC?

- 4 top events typically give a very large number of hard jets, which makes it very difficult to reconstruct.

- A recent study concluded we can, but the method was 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

  - In our case, it requires us to reconstruct at least 3 or 4 tops, which will significantly reduce the number of useful events.
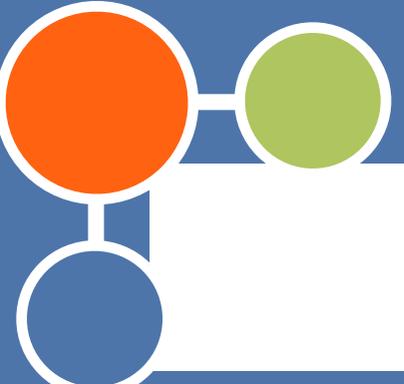
Four top-like ?

- We went with a more conservative approach, which required at least 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 can look at the shape of several kinematical distributions to show it looks "4 top-like".

- We simulate everything through MadGraph-MadEvent-PYTHIA-PGS-ROOT.

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).
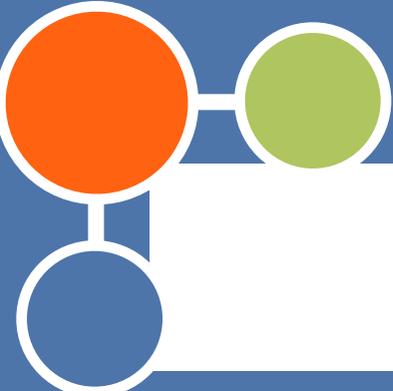
Cuts

- 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.

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 we can settle for a few observations that the signal looks more 4top-like or 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
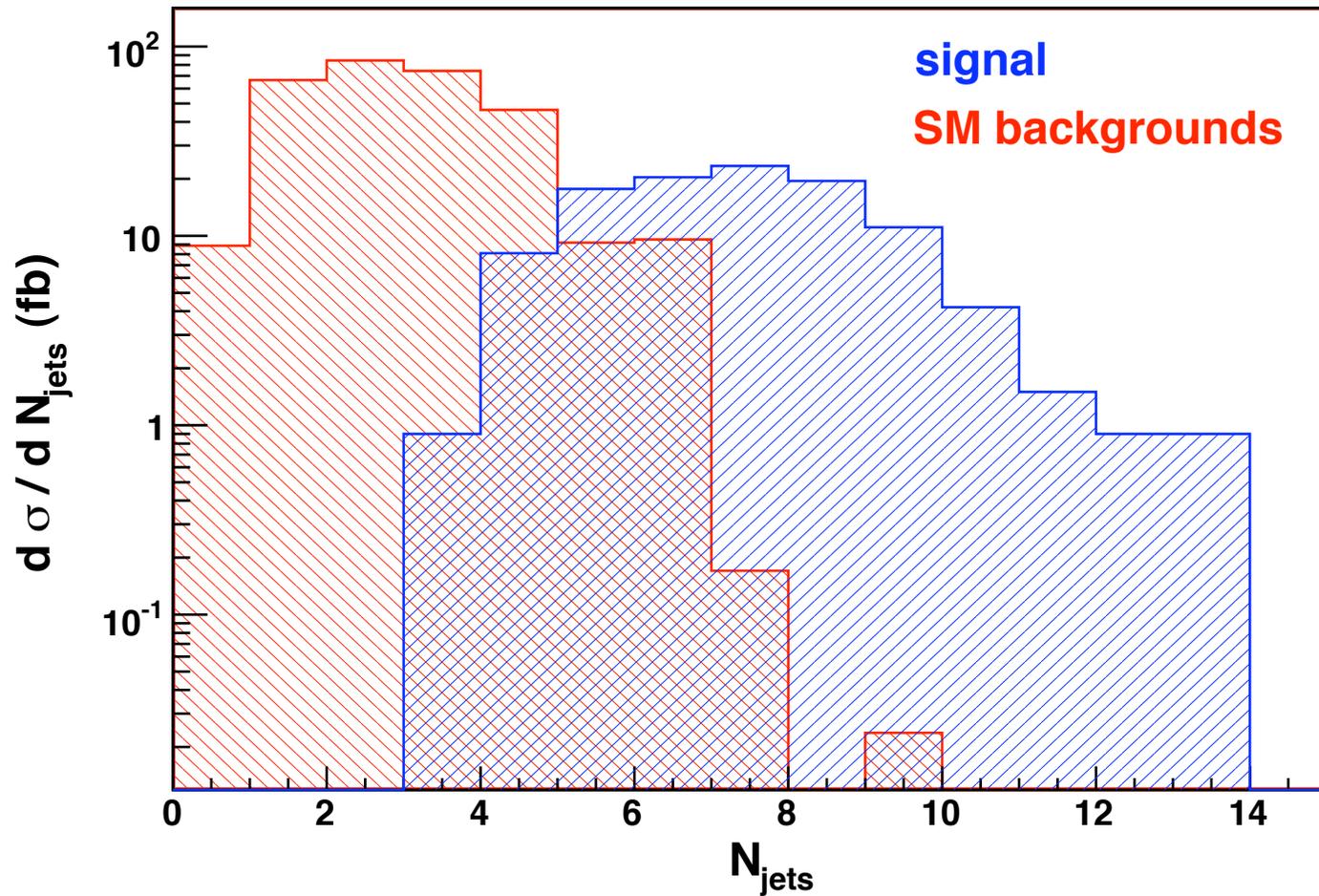
Our tops aren't tremendously boosted.

Number of b-tags
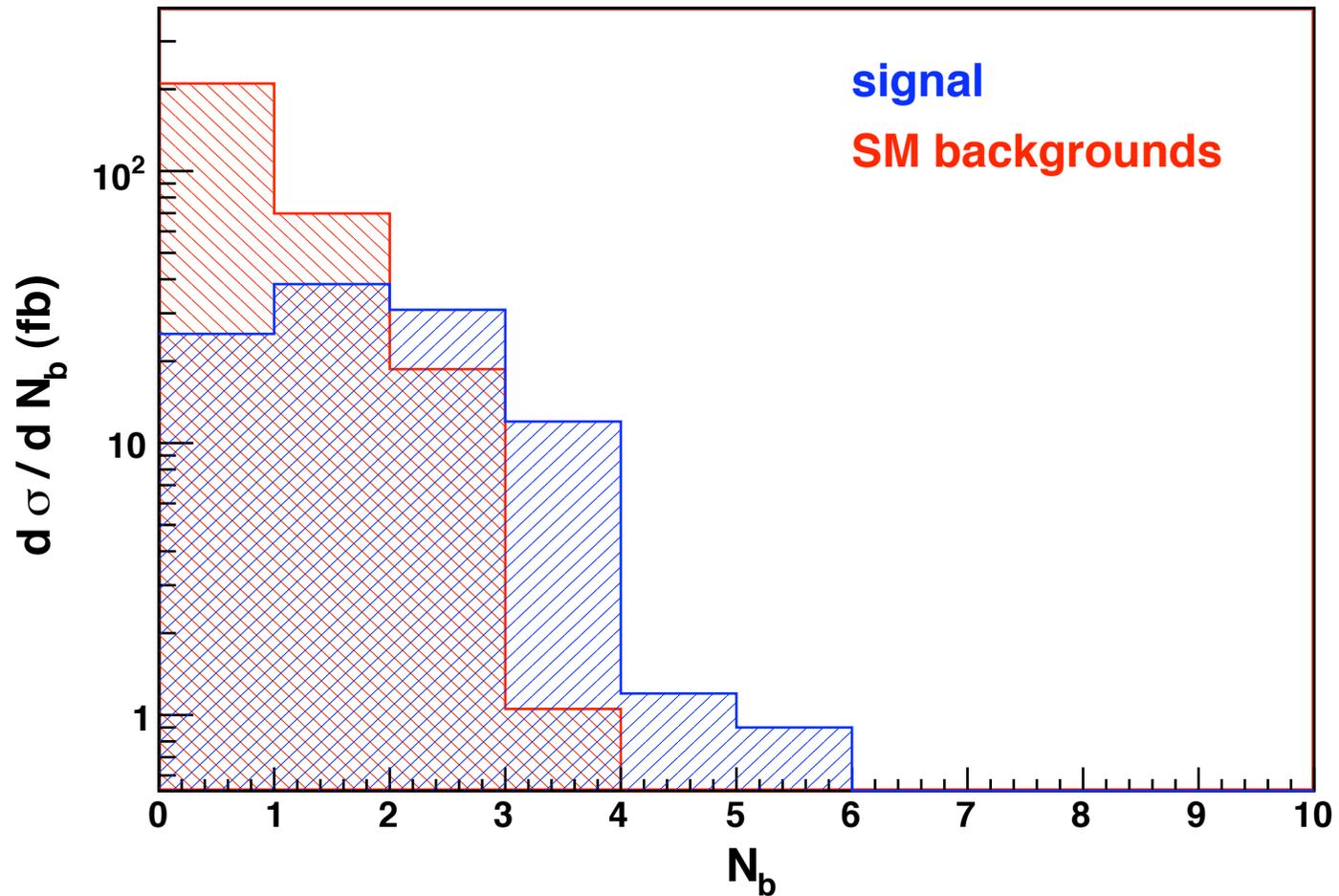
H_t Distribution
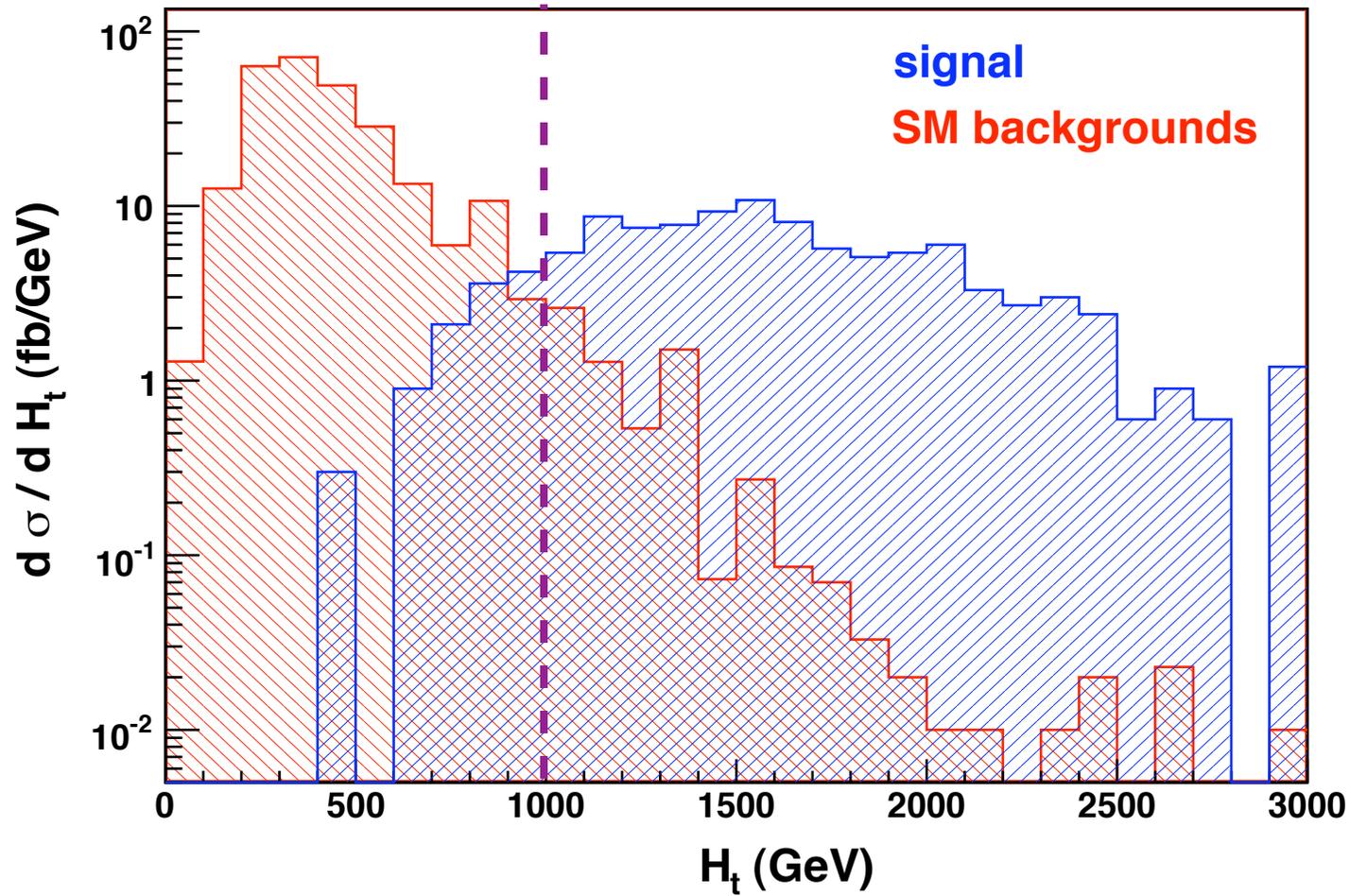
Future Directions?

- 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, 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?
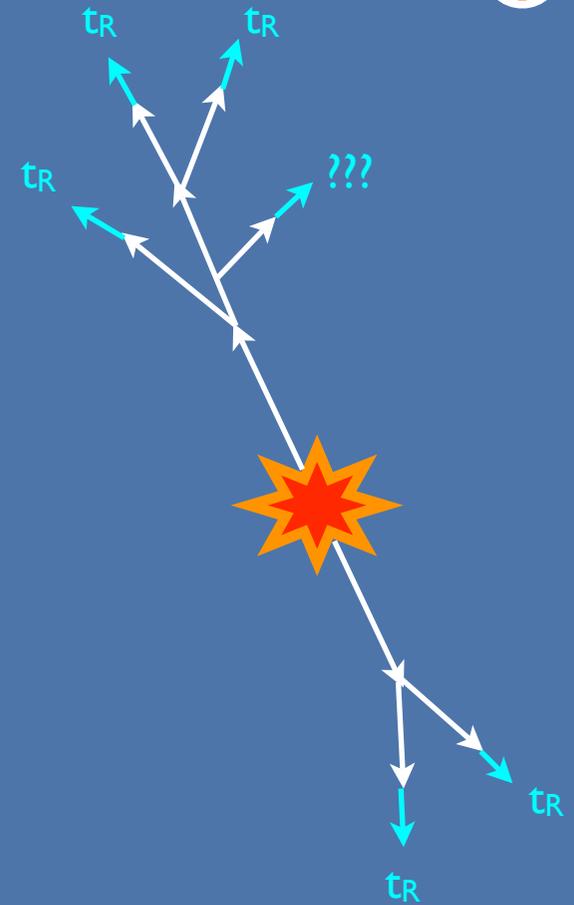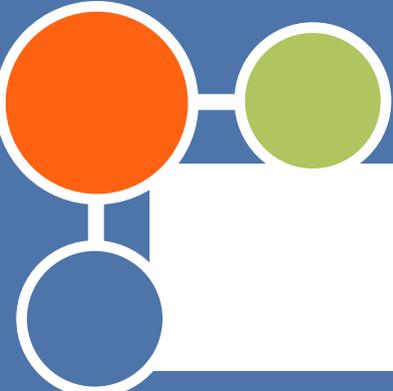
Future Directions?

- Even without going to the direct production of preons. The first layer might have a very broad width and overlap with high layers, which has a nontrival spectrum density and form factor of the vertices to the top.

- Those effects will change the momentum dependence of the amplitude and affect the angular distribution of the top in the end.

  - For the situation of leptons, see   Eichten, Lane, Peskin PRL50, 811 (1983)

- Could we really use those variables to know more on the strong dynamics?

- The key question is really how well we can reconstruct those top quark in ttbar? under what conditions? I am very curious about that.
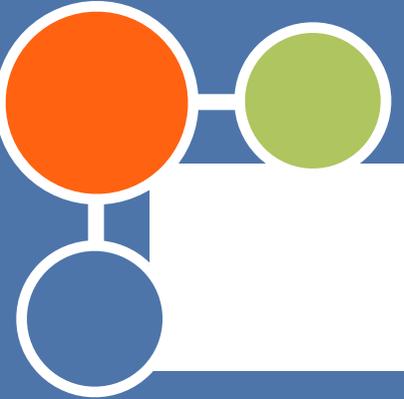
Conclusion

- 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!

Supplemental Slice

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.

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

5 pb^{-1} of (simulated) ATLAS data

T LeCompte

$\Lambda = 4\,\text{TeV}$
$g^2 = 4\pi$

Events/40 MeV

Jet E$_T$

GeV

Eichten, Lane, Peskin PRL50, 811 (1983)

Wow!

Tom LeCompte actually generated the previous plot by miscalibrating the energy of the high p_T jets by about 10%.
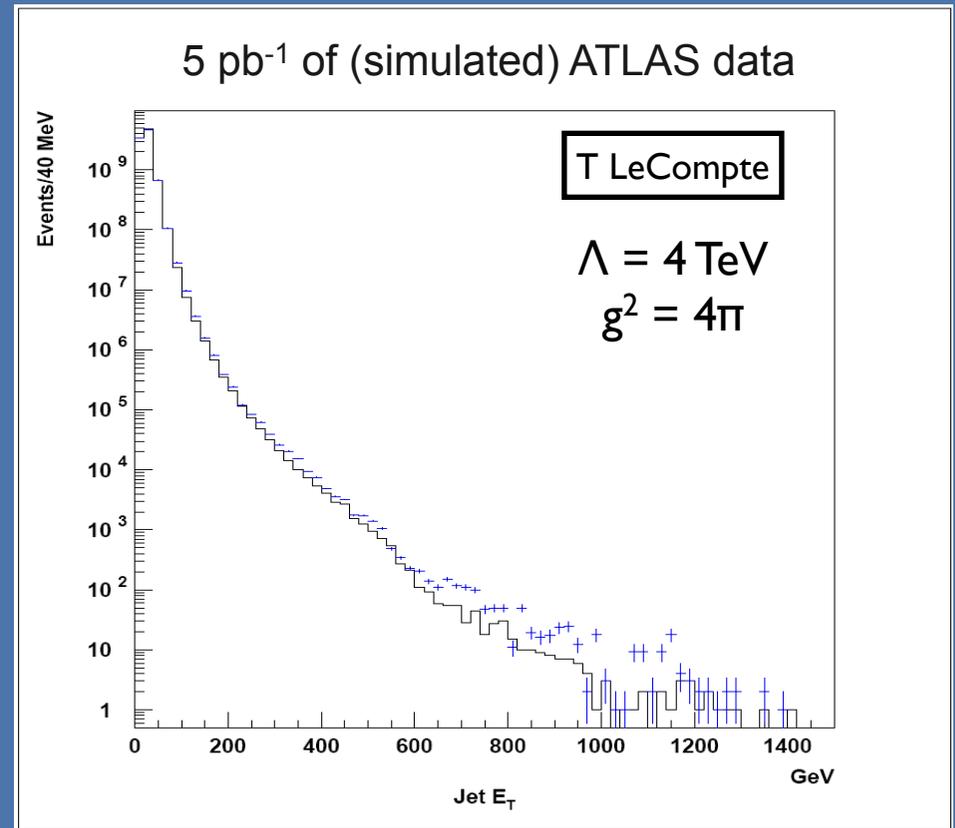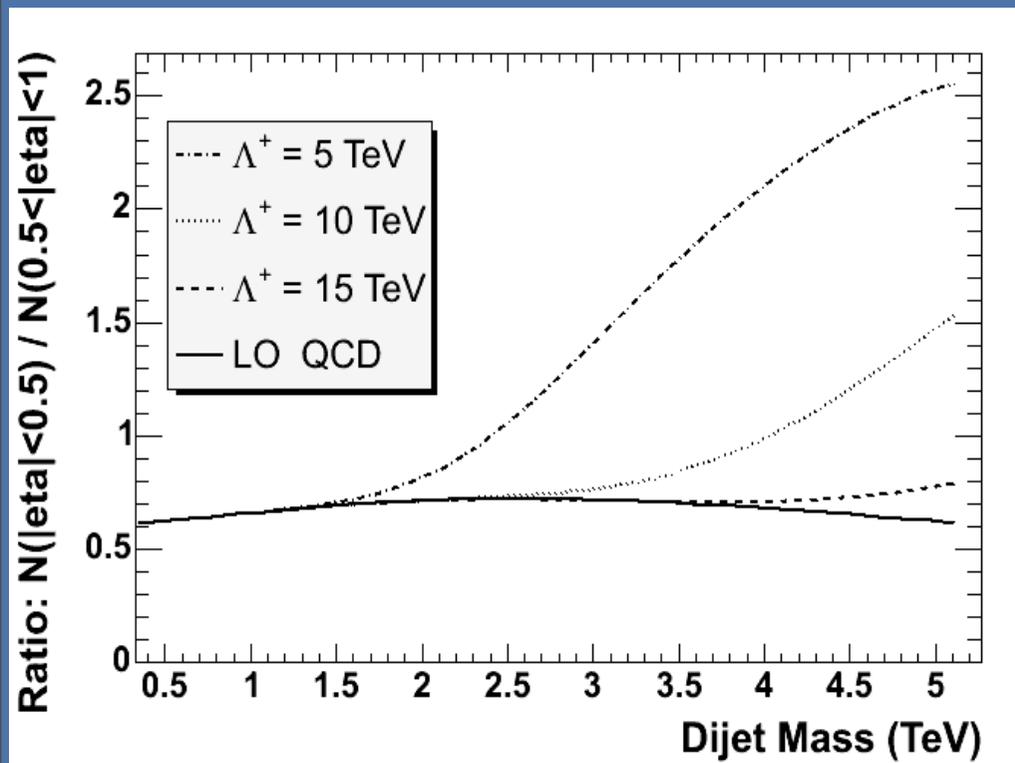
But discovery is still possible by looking at shape distributions.
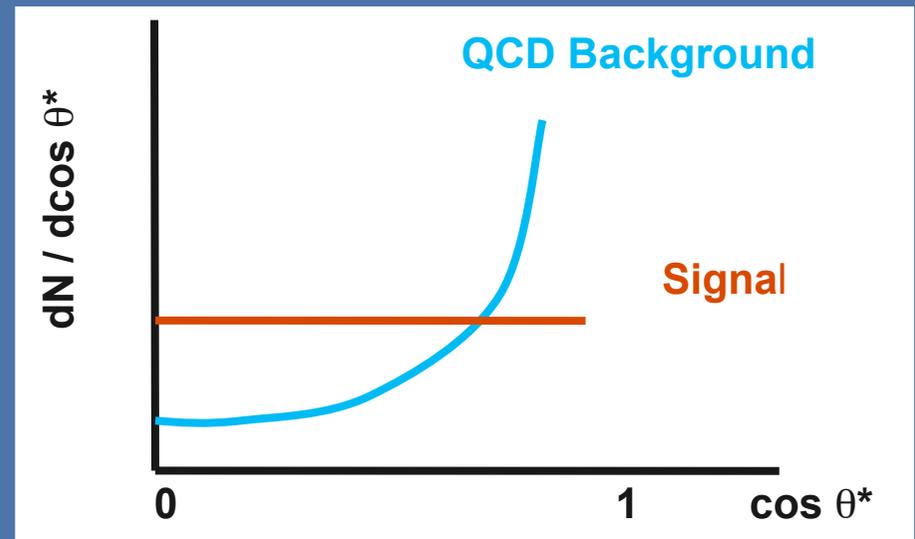
Compositeness at the LHC?

- 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 like techicolor, deconstructed moose and warped extra dimenison models in the past.

- At sufficeint high energy scale, can we see the constitutes ("preon")?
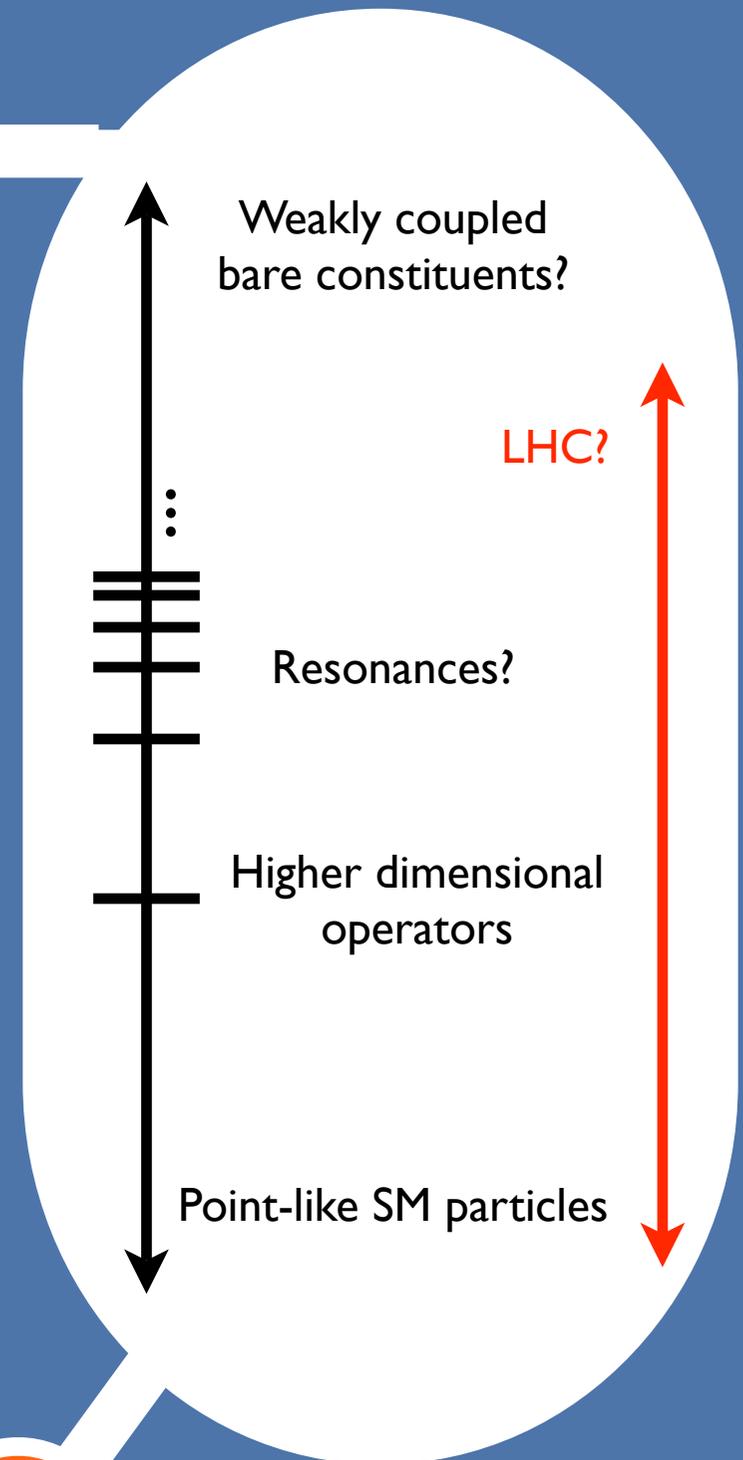
Weakly coupled bare constituents?

LHC?

Resonances?

Higher dimensional operators

Point-like SM particles

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$\bar{\text{q}}$ 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.


p $\bar{\text{p}}$

$\sqrt{\text{S}}$ = 1.96 TeV

SM
Λ = 500 GeV
Λ = 1 TeV

Color Singlet Operator

dσ / dM

M (GeV)

Alwall et al, JHEP 0709, 028 (2007)

$M_{t\bar{t}}$
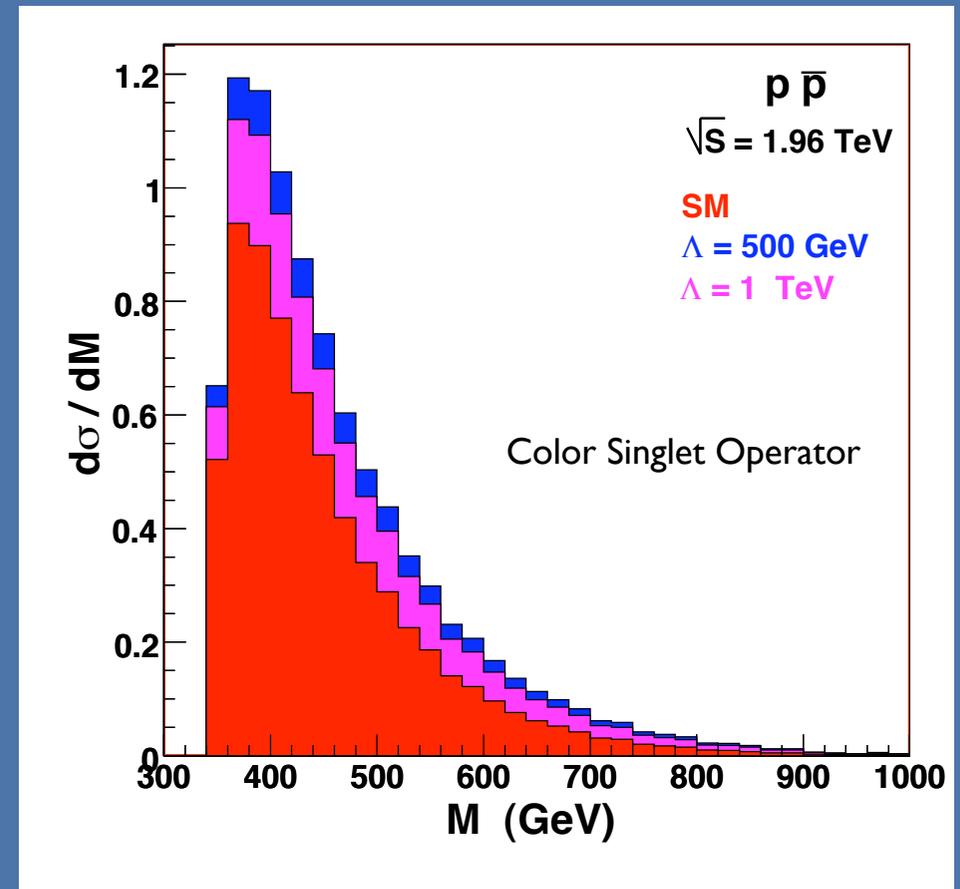
- CDF (and D0) do have results for top pairs binned in the invariant mass.

- 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.

Total Invariant Mass of the $t\bar{t}$ System

CDF Run II Preliminary, L=955 pb^{-1}

Data
SM $t\bar{t}$
non-top Background

CDF, arxiv:0710.5335 [hep-ex]

Number of Events

$M_{t\bar{t}}$ [Gev/c^2]
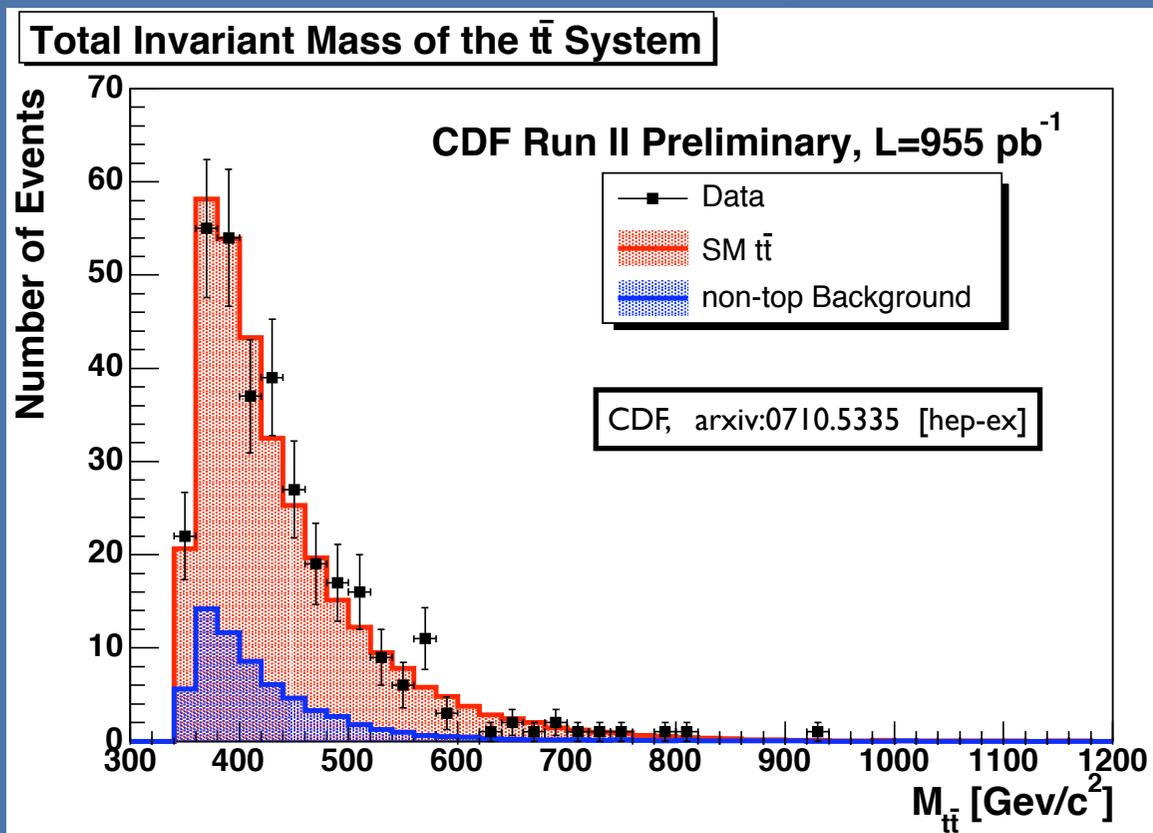
CDF uses this data to put a bound on narrow resonances decaying to top pairs.

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).

Backgrounds

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

Other 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 $\tilde{g} \rightarrow \tilde{t}\bar{t} \rightarrow t\bar{t} + \tilde{\chi}^0$ 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