Top Production and Decay

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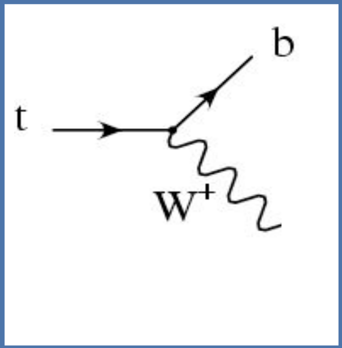
Outline

- Top Decays
- Top Pair Production
- Single Top
- Outlook

Top Decays

Top Decays

- Top decays through the electroweak interaction into a W boson and (usually) a bottom quark. Decays into strange or down quarks are suppressed by the small CKM elements V_{ts} and V_{td}.



$$\Gamma_t = \frac{G_F\, M_{\rm top}^3}{8\pi\sqrt{2}} \; |V_{tb}|^2 \left(1 - \frac{M_W^2}{M_{\rm top}^2}\right)^2 \left(1 + 2\,\frac{M_W^2}{M_{\rm top}^2}\right)$$ ~ 1.5 GeV

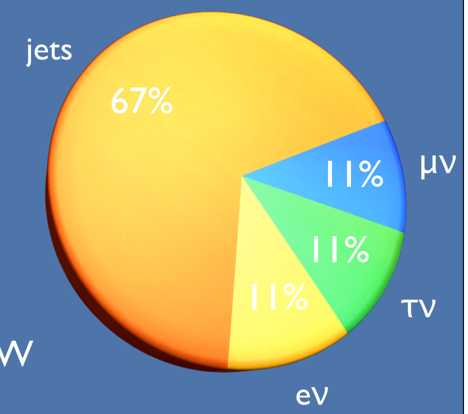
- Top is the only quark heavy enough to decay into a real (on-shell) W boson.

- The experimental signature is a jet containing a bottom quark and the W decay products. The W boson decays into all of its possible final states ($e\nu$, $\mu\nu$, $\tau\nu$, or jets).

Top Decays

- Since the decay into Wb occurs very close to 100% of the time, we classify top decays by how the W boson decays.
- The relative branching ratios are easy to predict:
  - The W couplings are universal.
  - Light fermion masses are all small compared to M_W
  - CKM elements are nearly diagonal.
  - Counting three colors each of ud and cs:

$$BR(W \to e\nu) : BR(W \to \mu\nu) : BR(W \to \tau\nu) : BR(W \to \text{jets} = 1 : 1 : 1 : 6$$



Top Decays

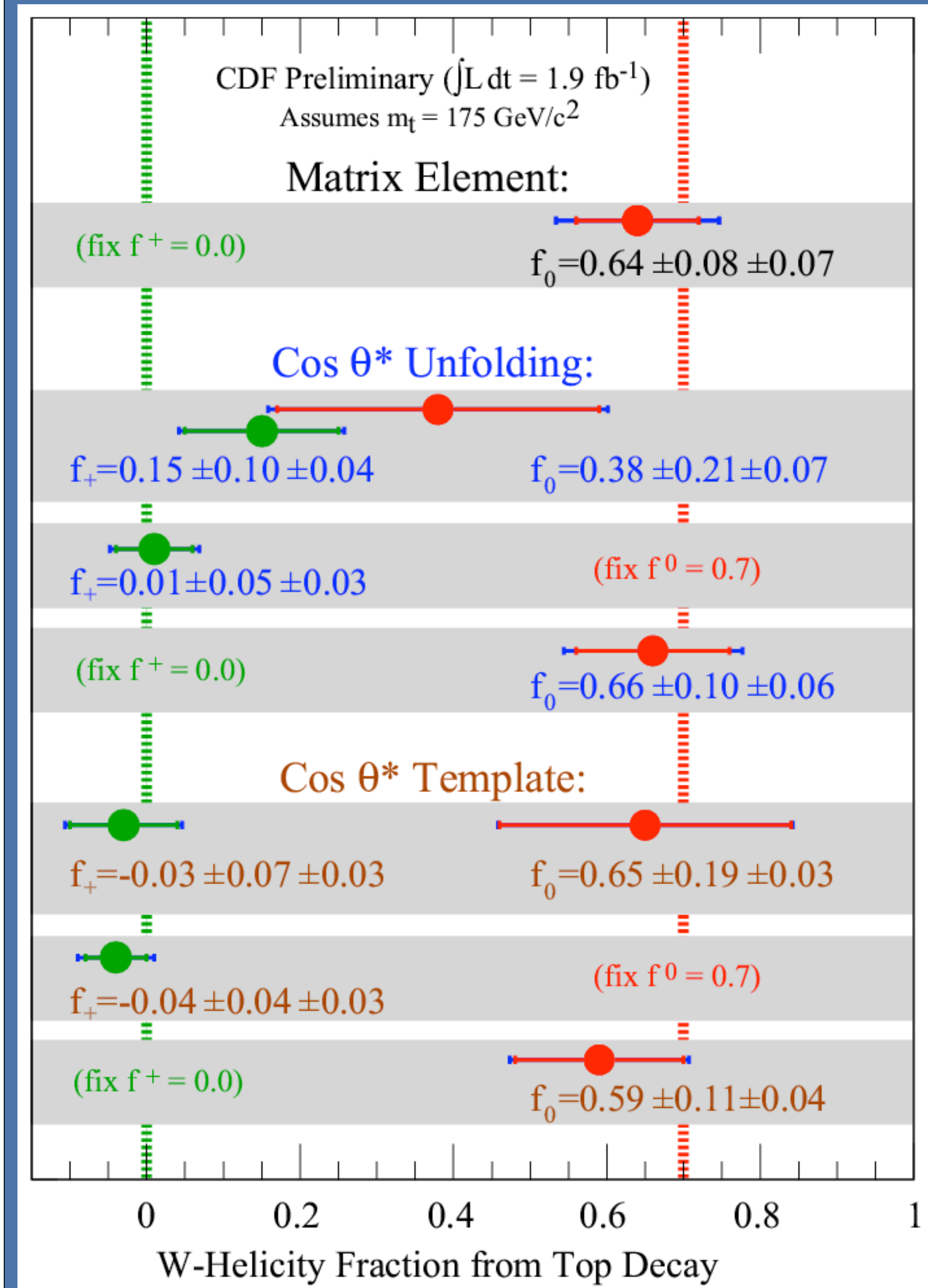
- In the SM, top has a Branching Ratio into $W^{+}b$ very close to 100%.
- Top decay represents our first glimpse into top's weak interactions. In the SM, it is a left-handed interaction: γ^{μ} **(1 - γ_5)**.
- Because the decay width is typically smaller than energy resolutions, the decay works better to measure the structure of the decay, rather than its magnitude.
- Top is the only quark for which $\Gamma_t >> \Lambda_{QCD}$. This makes top the only quark which (in some sense) we see "bare".
  - Top spin "survives" non-perturbative QCD - soft gluons cannot scramble its spin before it has time to decay!

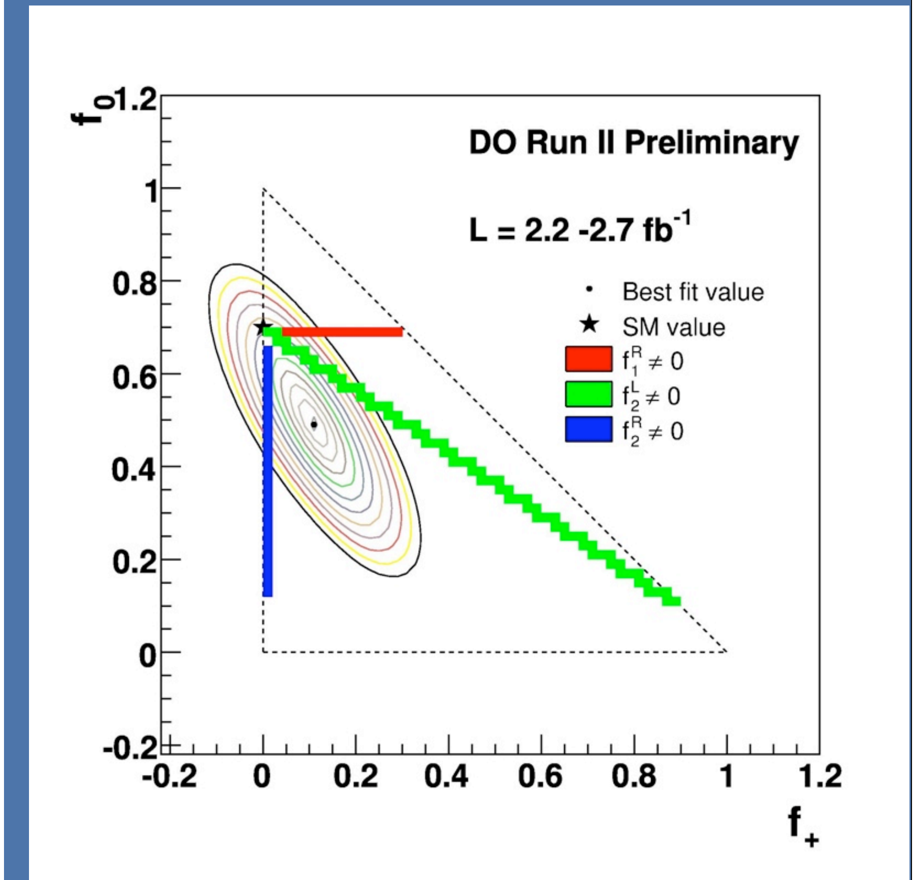
W Polarization

- The left-handed W-t-b vertex produces polarized W bosons (either left-handed or longitudinal). The ratio depends on m_t and M_W:

$$f_0 \equiv \frac{\#\ \text{longitudinal W's}}{\text{Total}\ \#\ \text{W's}} = \frac{m_t^2}{2M_W^2 + m_t^2}$$

- The W polarization is correlated with the direction of p_e compared to the direction of p_b in the top rest frame.
- The *W* polarization is independent of the parent top polarization. Thus, it is a good test of the left-handed *W*-*t*-*b* vertex structure and can be measured with large statistics from QCD production of top pairs.



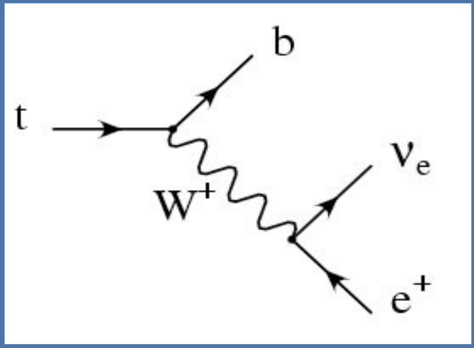


Consistent with SM expectations with moderate error bars...

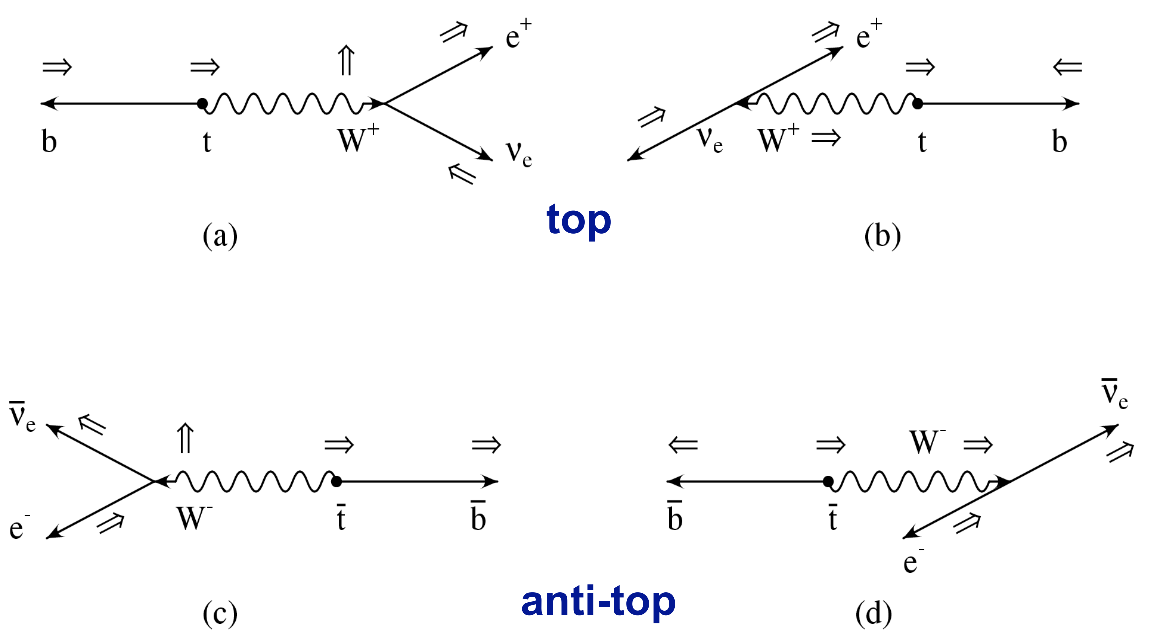
New Physics usually results in deviations at the <10% level.

Top Polarization

- Because the top decays through the left-handed weak force, it analyses its own polarization through its decay products.
- In a charged lepton decay, the charged lepton tends to move in the direction of the top polarization - giving an indication of the top polarization direction.

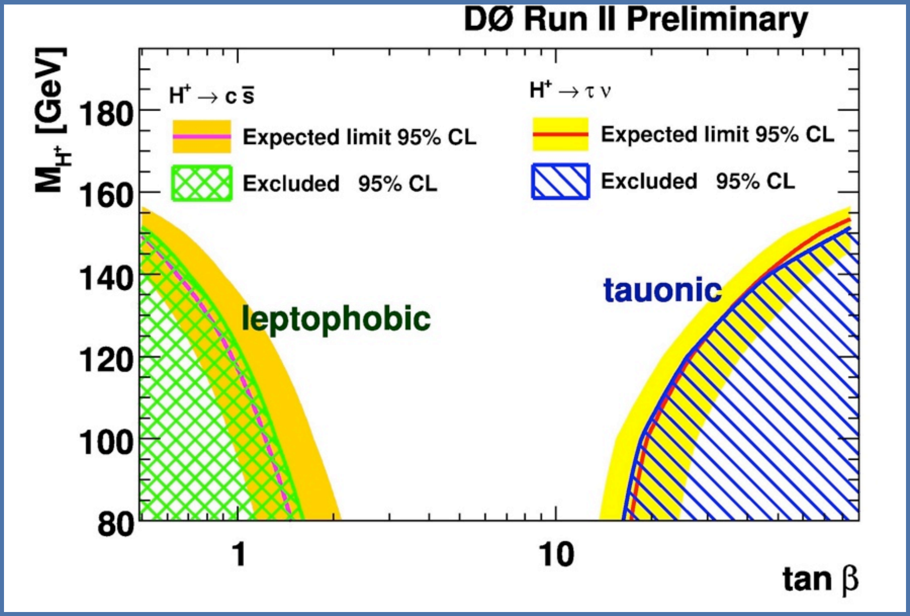


We can use single top production in the SM to test these ideas: the SM itself provides a source of polarized top quarks.



Decay into H^+b?

- In a theory with extra Higgs doublets, there will be more physical Higgs scalars.
- For example, in a model with two Higgs doublets (as minimal SUSY models), there will be a pair of charged Higgses, and three neutral Higgs after EWSB.
- Because the fermion masses come from interactions with the Higgs, the 3rd generation (and top particularly) generically couples much more strongly. For example in SUSY:



$$H^+\text{-t-b coupling}: \left(\frac{m_t \cot\beta}{v} P_R - \frac{m_b \tan\beta}{v} P_L \right)$$

$$\tan\beta \equiv \frac{\langle H_1 \rangle}{\langle H_2 \rangle}$$

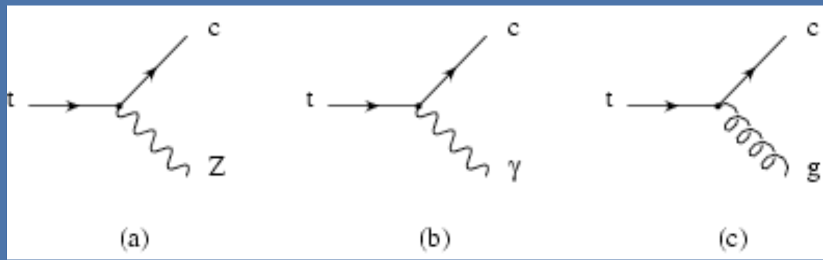
At high $\tan\beta$, H^+ decays to $\tau\nu$.
At low $\tan\beta$, H^+ decays to cs.

FCNC Decays

- Another exotic decay possibility are FCNC decays of the top quark into up or charm.
- These decays are highly suppressed in the SM (BRs~10^{-9} or smaller), and thus would be a clear sign of new physics at the LHC.
- BSM physics can contribute at tree level (Z + c or u) or loop level (γ or g + c or u).
- Higher dimensional operators describe the interactions:

$$\frac{g}{\Lambda^2} W_{\mu\nu} \left(H\bar{Q}_3\right) \sigma^{\mu\nu} c_R \rightarrow g\kappa^Z_{tc}\; Z_\mu\; \bar{t}\gamma^\mu c_R$$

$$\kappa^Z_{tc} \equiv \frac{m_t^2}{\Lambda^2}$$



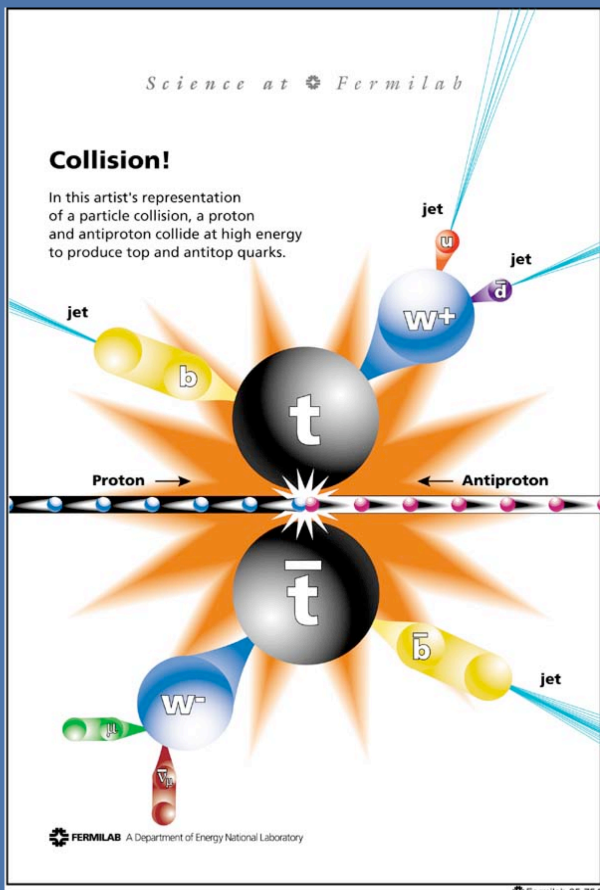
Run II CDF bounds:

BR(t->Zc) < 13%,
BR(t->gc) < 12%,
BR(t->γc) < 18%

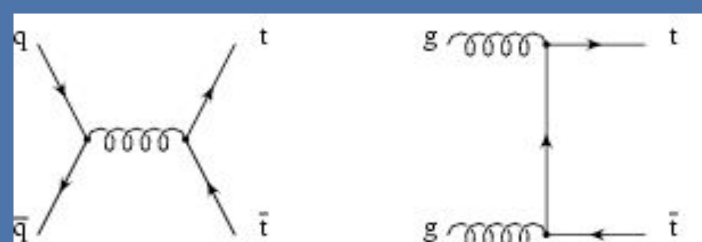
The huge top sample at LHC is opportunity to see very rare processes involving top!

Top Pair Production

$t\bar{t}$ Production

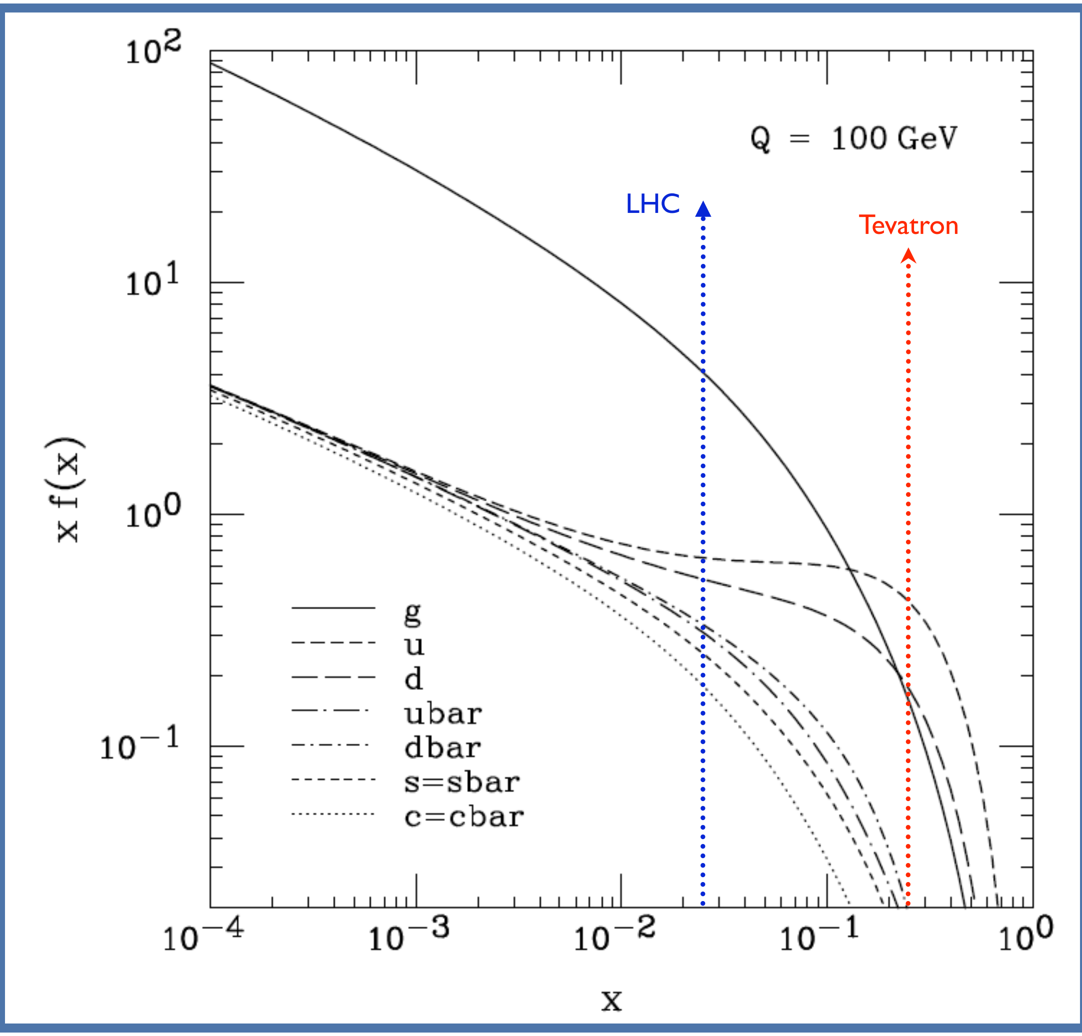


- At a hadron collider, the largest production mechanism is pairs of top quarks through the strong interaction.
- (Production through a virtual Z boson is much smaller).
- At leading order, there are gluon-gluon and quark-anti-quark initial states.



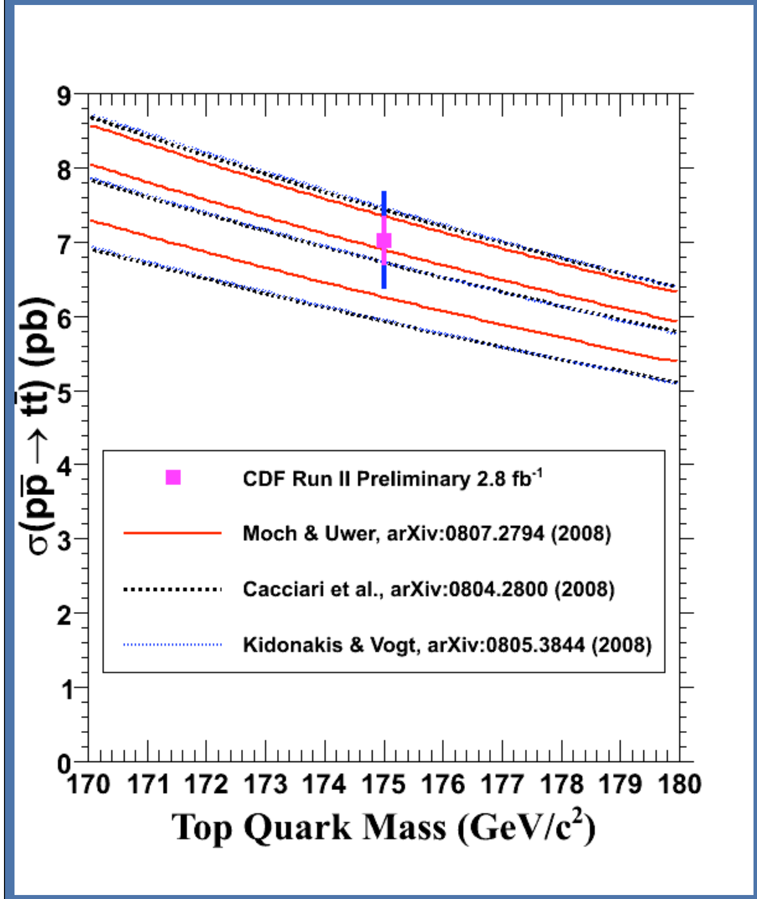
- At Tevatron, qq dominates (~85%).
- At LHC, gg is much more important.

PDFs



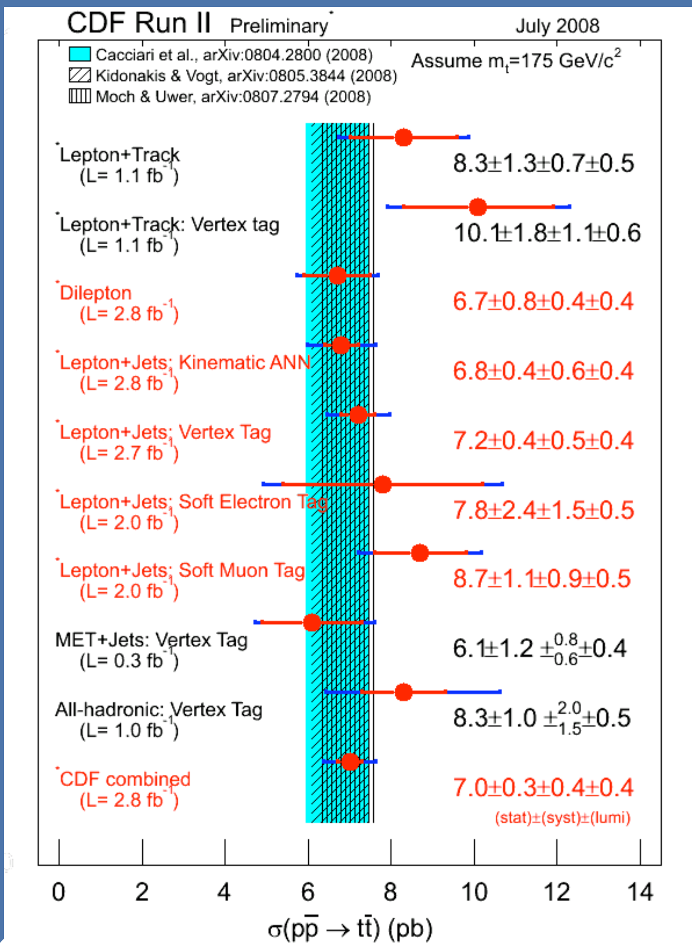
Q = 100 GeV
LHC
Tevatron
x f(x)
x
g
u
d
ubar
dbar
s=sbar
c=cbar
10^2
10^1
10^0
10^{-1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0

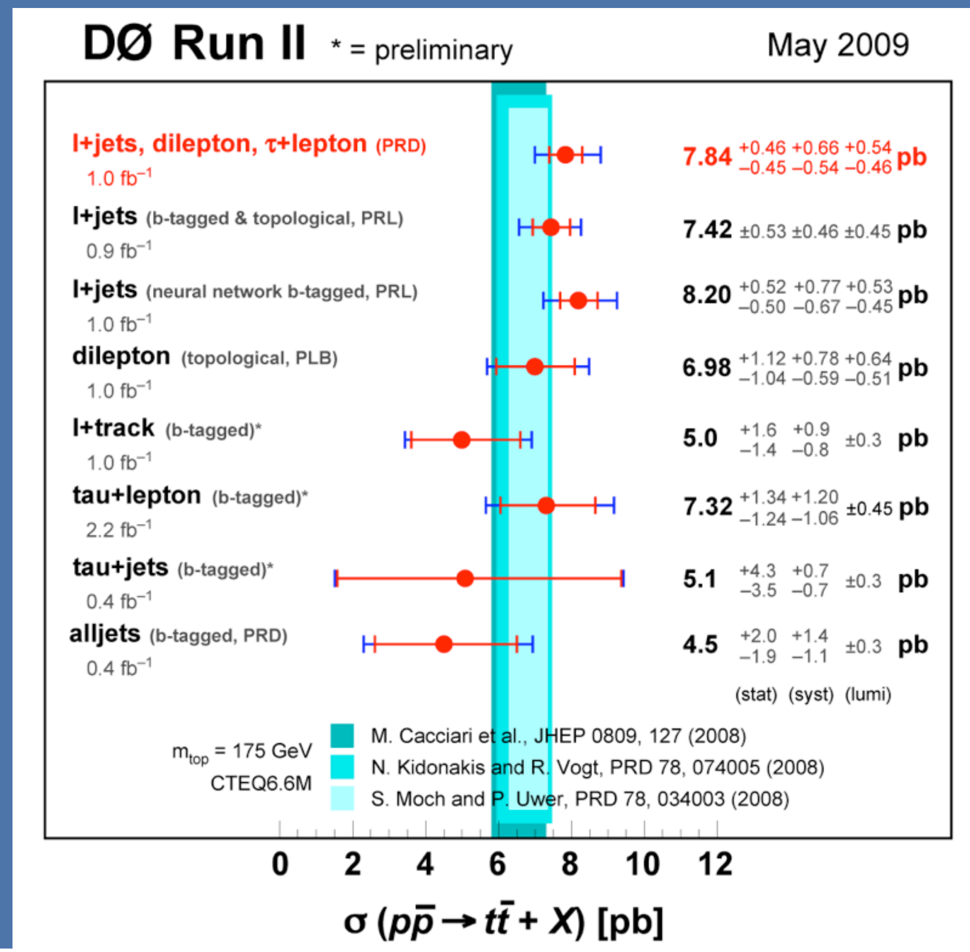
$t\bar{t}$ Production Rates



- Theory predictions for top pair production are known up to NLO.
- The most sophisticated predictions have threshold corrections from soft gluons resummed.
- The cross section at LHC is of order 800 pb, and is a major source of background to electroweak searches.
- At the LHC, the theory uncertainties in the over-all rate are of order 10%, largely from scale dependence.
- The cross section correlated with the mass provides a test of the SM.

$t\bar{t}$ at the Tevatron



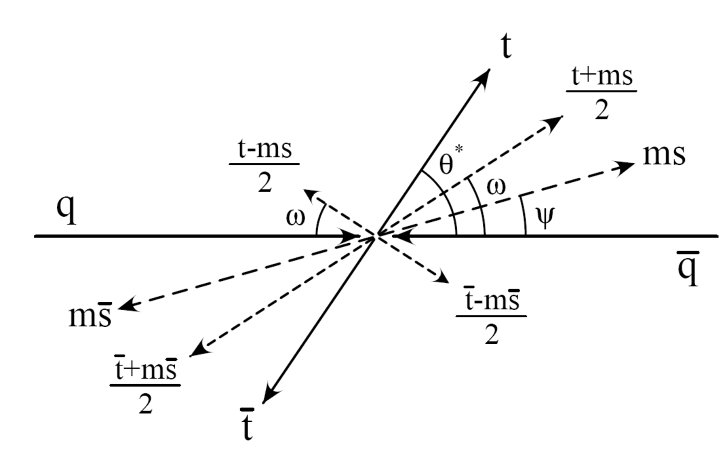


t-tbar Spin Correlations

- In the qq initiated sub-process, the spin of the top and the anti-top are correlated because the intermediate particle is a vector (gluon).
- If the top were massless, this would result in perfect anti-alignment of the t and anti-t spins.
- However, most tops are produced close to threshold, for which the helicity basis is not optimal.
- In that case, the basis along the beam axis is better because it takes advantage of the (massless) q & qbar polarizations.
- The correlations are maximized if one chooses to define the spin along the axis ψ defined by:

$$\tan\psi \equiv \frac{\beta^2 \sin\theta^* \cos\theta^*}{1-\beta^2\sin^2\theta^*}$$

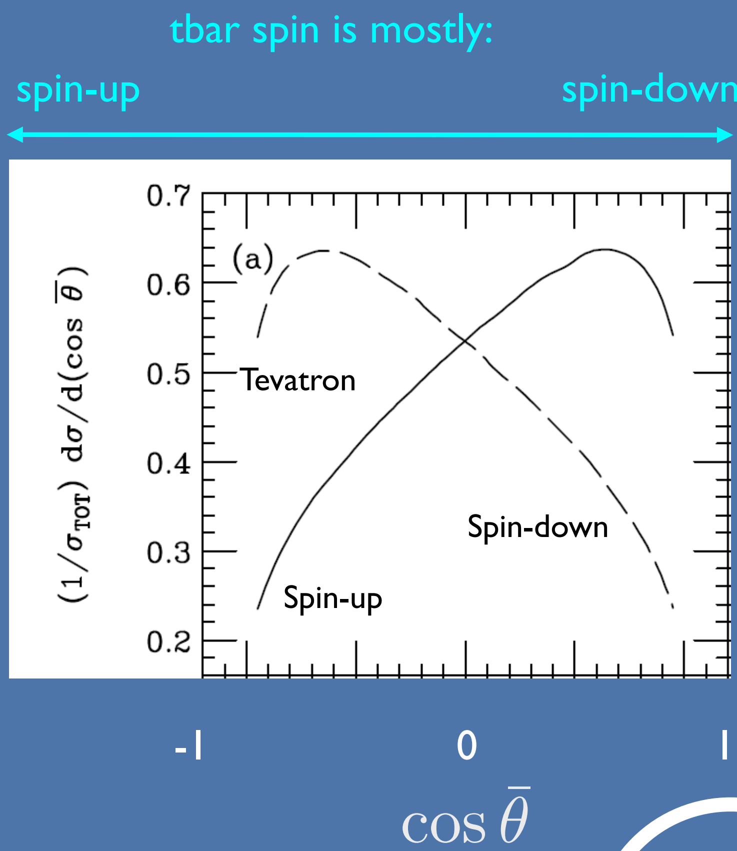
- This interpolates between the two bases and results in the cleanest separation between spin-up and spin-down tops.



G Mahlon S Parke
PLB411, 173 (1997)

Spin Correlations

- At LHC, the effect is somewhat washed out by the dominance of the gg initial state.
- At Tevatron, q qbar dominates and the optimal basis results in a 92% spin correlation.
- This result is intimately tied to the SM tt production mechanism. If there is physics beyond the SM in tt production, one could see it as a break-down of the expected distributions.
- (However, because the ψ basis itself makes heavy use of the SM physics, it is difficult to use to identify the new physics).
- To make practical use of it, one must further see how it is washed out by actual observables such as the direction of the charged lepton momentum in a top leptonic decay.



Angle between the tbar spin and e momentum

Top Pairs Beyond the SM

- New Physics can affect the production of top pairs.
  - An interesting possibility is a resonance in the t tbar invariant mass distribution.
- I'll go through a few models that contain objects we expect to see that way, and then show some of the measurements we can do once we discover one...

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)

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

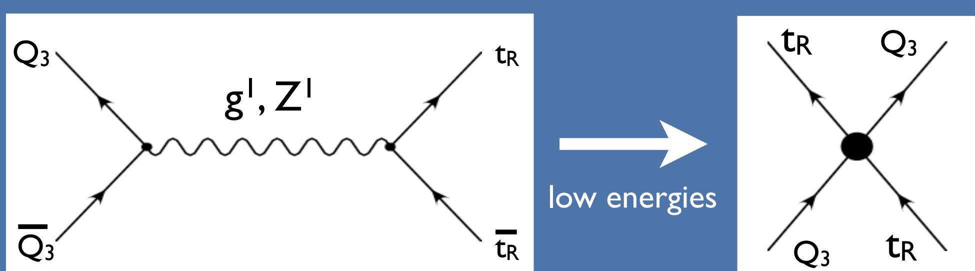
(color singlet, SU(2) doublet, Y=+1)

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

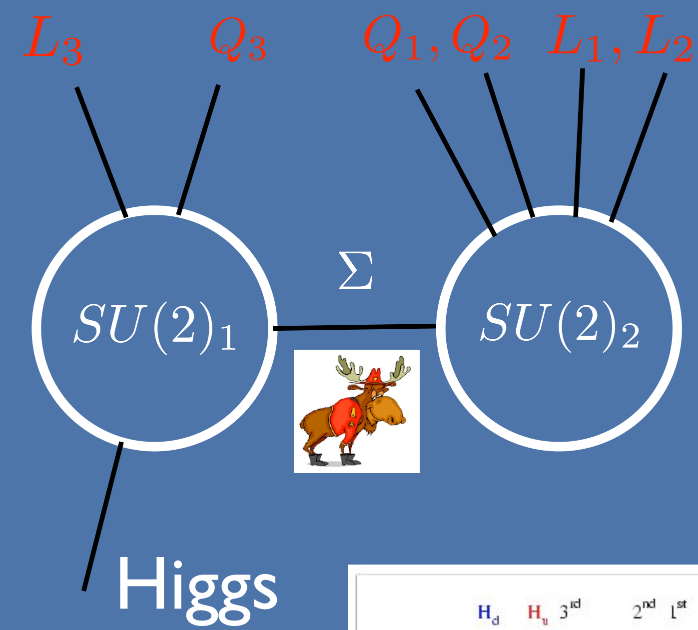
- So we invariably have a ~TeV mass gluon-like object (and often a Z' too) which couples strongly to top!

Chivukula, Simmons, Terning PRD53, 5258 (1996)
Muller, Nandi PLB383, 345 (1996)
Malkawi, Tait, Yuan PLB385, 304 (1996)

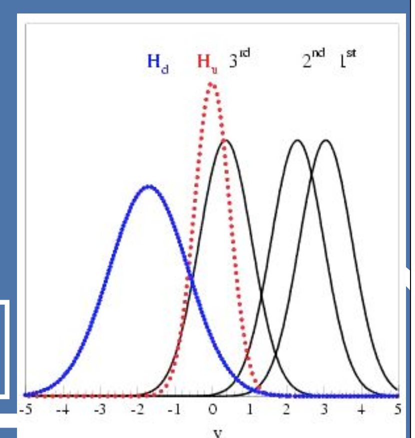
Top-flavor

- Top-flavor expands the weak interactions into an SU(2) for the third generation, and one for the first and second generations. So we have a pair of W's and a Z'.
- The ordinary weak interactions are the diagonal subgroup (and are close to family universal).
- Dimensional deconstruction suggests this has similar physics to an extra-dimensional theory of flavor.

Hill, Pokorski, Wang PRD64, 105005 (2001)
Arkani-Hamed, Cohen, Georgi, PRL86, 4757 (2001)



Kaplan, Tait
JHEP0006, 20, (2000)



Top-flavor

- Each SU(2) has two charged and one neutral gauge boson associated with its generators. $W_1^{\pm}, W_1^0, \quad W_2^{\pm}, W_2^0$
- When the Higgs Σ gets an expectation value (u), it breaks SU(2)xSU(2) down to a "diagonal" SU(2) whose generators are a linear combination of the original generators.

$$\begin{bmatrix} W \\ W' \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \end{bmatrix}$$

$$g_1 = \frac{g}{\sin\phi} \quad g_2 = \frac{g}{\cos\phi} \qquad M^2_{W',Z'} = \frac{g^2}{2\sin^2\phi\cos^2\phi} u^2$$

- This residual symmetry is identified with our usual Electroweak force (Ws and Z). The broken combinations become massive and are new states (W' and Z'), not found in the SM.

Interactions

- At extremely high energies, well above the W' and Z' masses, we can think in the original SU(2)1-SU(2)2 basis.
- In that limit, we see a different W and Z for the third family quarks and leptons from the W and Z that couples only to the first two families.
- At lower energies, I should think about the mass eigenstates (W and W' for example).
- The W (and Z) couple (approximately) universally to all of the fermions, regardless of family.
- The W' and Z', instead, reflect the fact that the third family is different, and have couplings which depend on the family.

enhanced $W' - t - b \ : \ (g \cot \phi) \ \gamma^\mu P_L$ $W' - u - d \ : \ (g \tan \phi) \ \gamma^\mu P_L$ suppressed

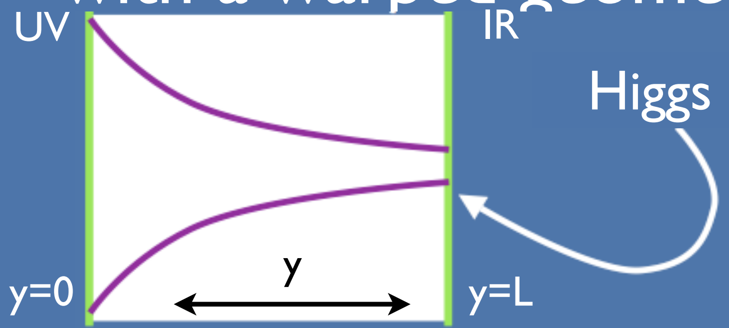
Topflavor

- 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)

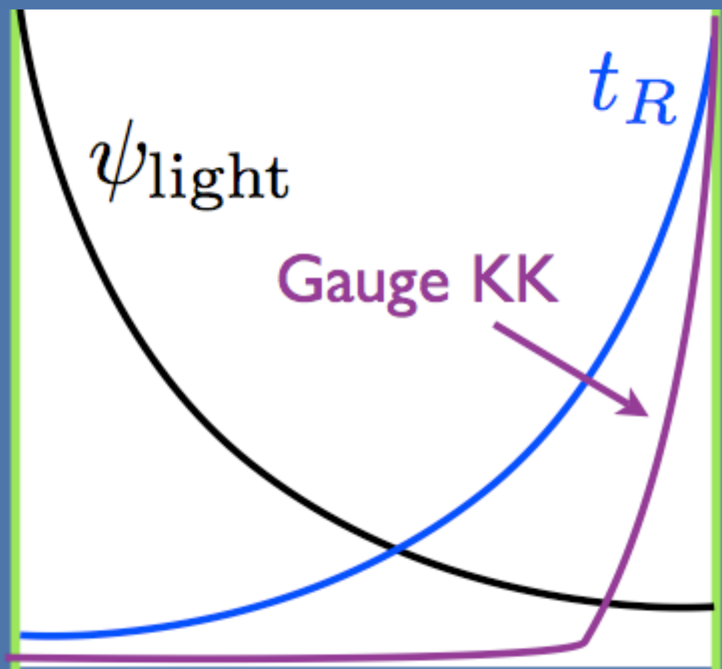


$$ds^2 = e^{-2ky}dx^2 - dy^2$$

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

- 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.

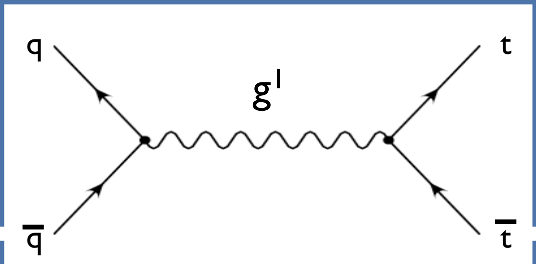
Top couples more strongly to KK modes!

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.

Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si, Soni, PRD76:115015,2007

- 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.
  - 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:



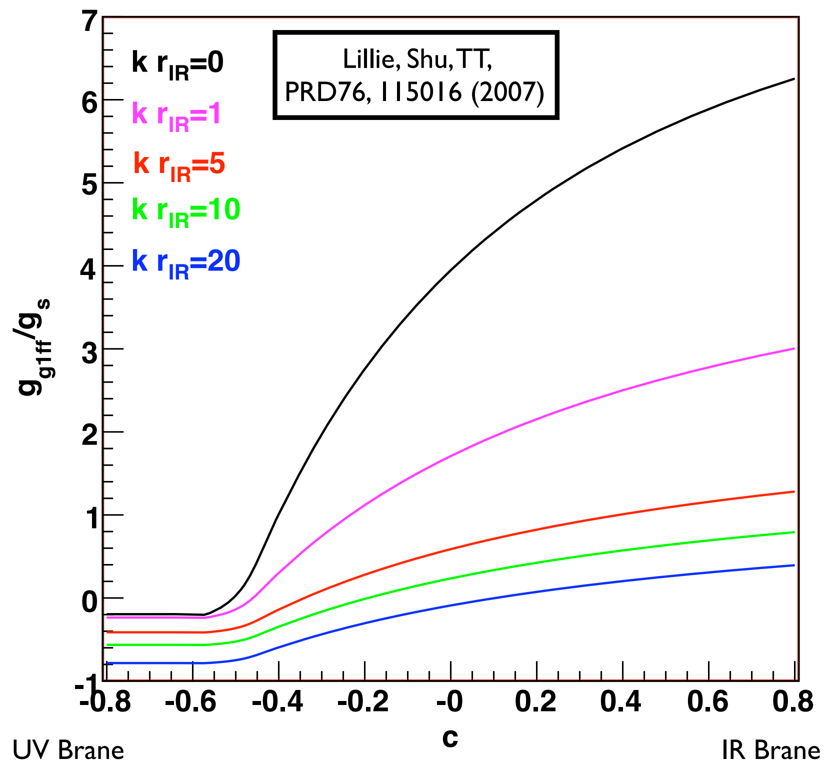
and decays into tops...

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)

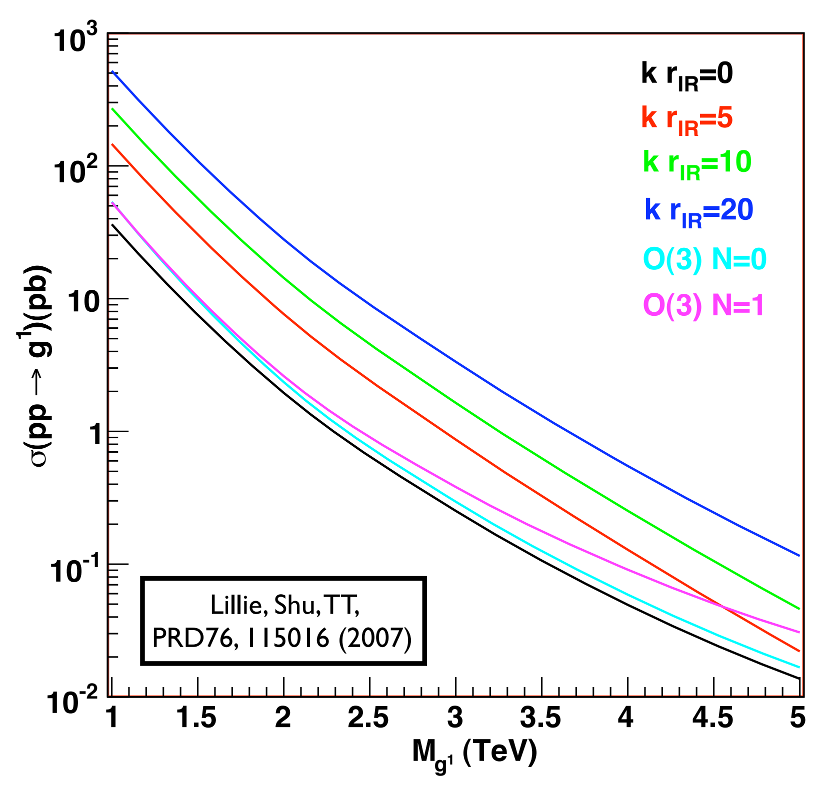
- The coupling is controlled by the quark wave functions, which are defined by a dimensionless parameter 'c'. (Their bulk mass is c k).



Cross Sections

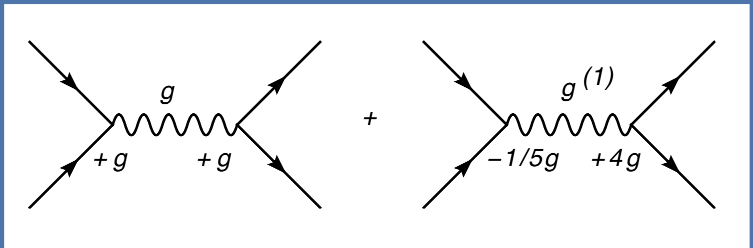
- Assuming the light quarks are mostly fundamental, the coupling to the first KK gluon is small but noticeable.
- The cross section and branching ratios depend sensitively on the couplings, and thus reflect the underlying the parameters.

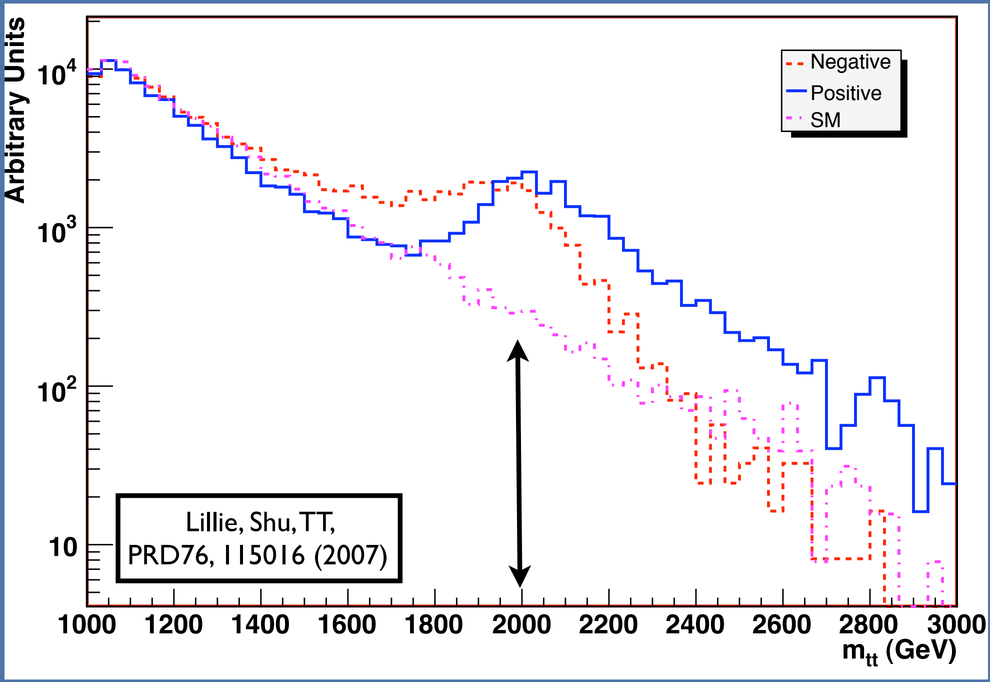
Model	top quarks	bottom quarks	light quarks	custodial partners	Γ_{g^1}/M_{g^1}
Basic RS	92.6%	5.7%	1.7%		0.14
$\kappa r_{IR} = 5$	2.6%	13.2%	84.2%		0.11
$\kappa r_{IR} = 20$	7.8%	15.1%	77.1%		0.05
$O(3)$, $N = 0$	48.8%	49.0%	2.0%		0.11
$O(3)$, $N = 1$	14.6%	14.6%	0.6%	70.2%	0.40



Width and Interference

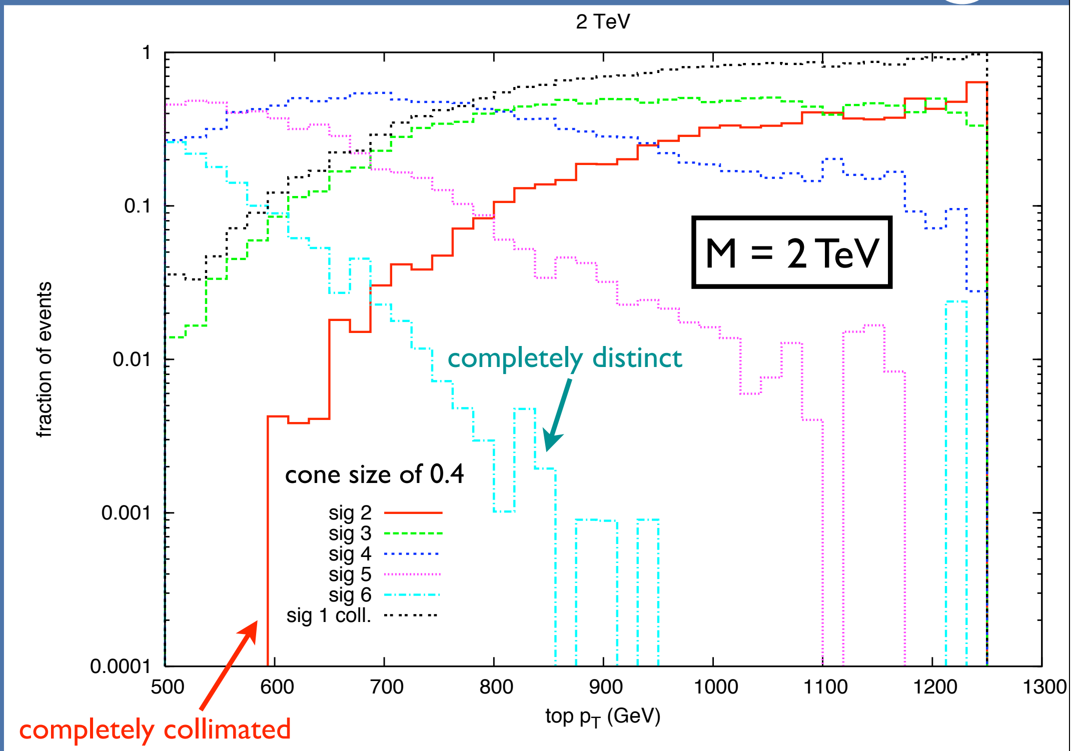
- In RS, as can be expected in any composite model, the KK gluons are strongly coupled, and have relatively large widths (~10% x M).
- The width may be directly measurable even with large LHC jet energy resolutions.
- Interference with the continuum $t\bar{t}$ background tells us about the relative sign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

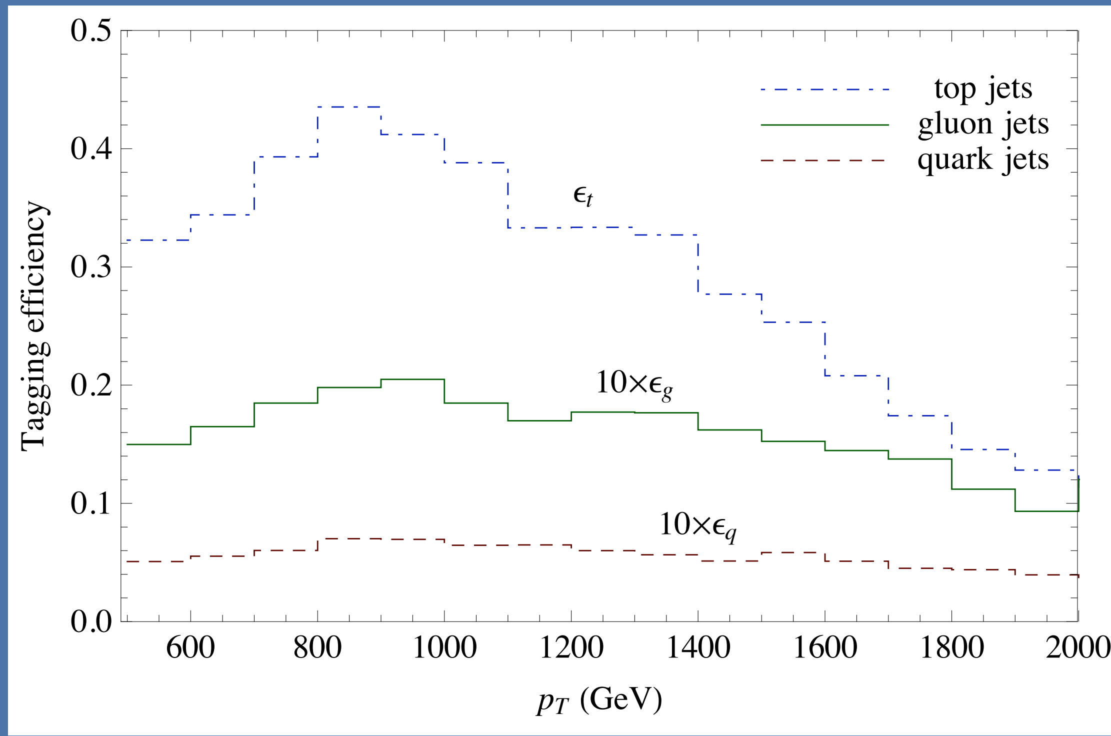
Jet Structure?

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.

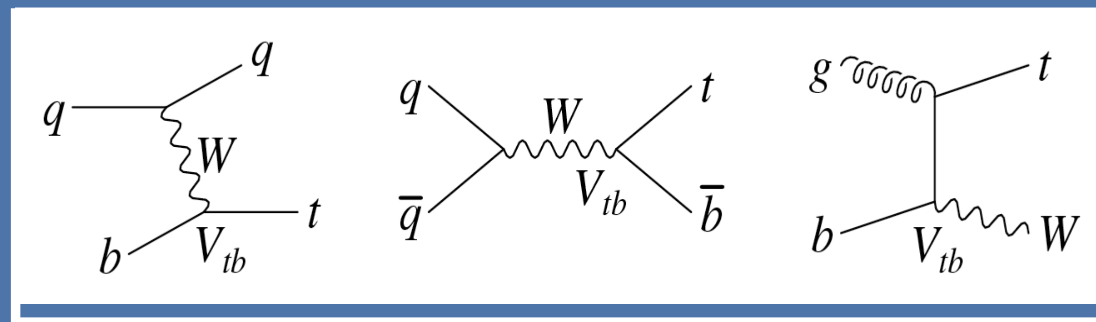
Thaler, Wang, JHEP 0807:092 (2008)
Almeida, Lee, Perez, Sung, Virzi, arXiv:0810.0934



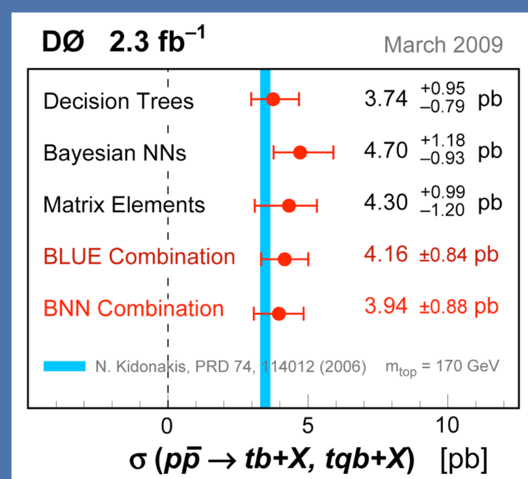
Single Top Production

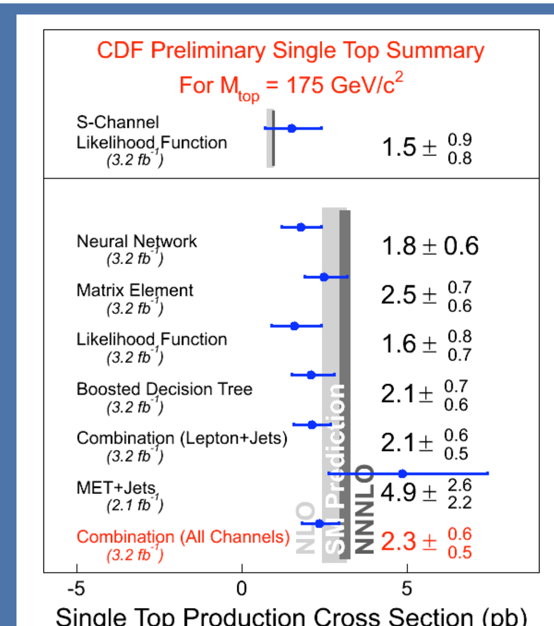
Single Top Production

- Top's EW interaction!
  - Three modes:
    - T-channel: q b → q' t
    - S-channel: q $\bar{q}$' → t $\bar{b}$
    - Associated: g b → t W^-



Observed at Tevatron!



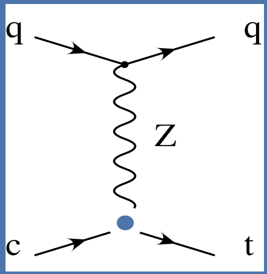


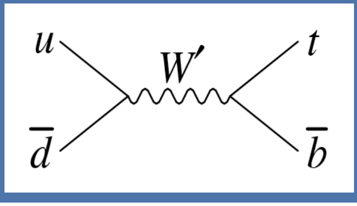
s- Versus t-Channels

- s-channel Mode
  - Smaller rate
  - Extra b quark final state
  - σs α |Vtb|2
  - Polarized along beam axis at Tevatron.
- t-channel Mode
  - Dominant at Tevatron
  - Forward jet in final state
  - σs α |Vtb|2
  - Polarized along spectator jet axis (Tevatron & LHC).

Mahlon, Parke PLB476 323 (2000); PRD55 7249 (1997)

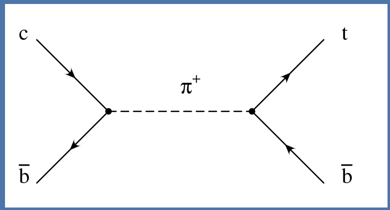
- Sensitive to resonances
  - Possibility of on-shell production.
  - Need final state b tag to discriminate from background.
- Sensitive to FCNCs
  - New production modes
  - t-channel exchanges suppressed





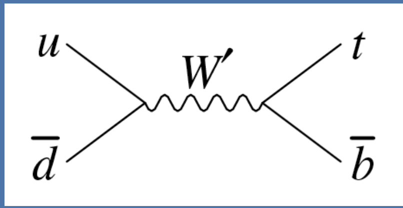
Charged Resonance

- Charged Higgs H+, Top-pion π+
- RH coupling!

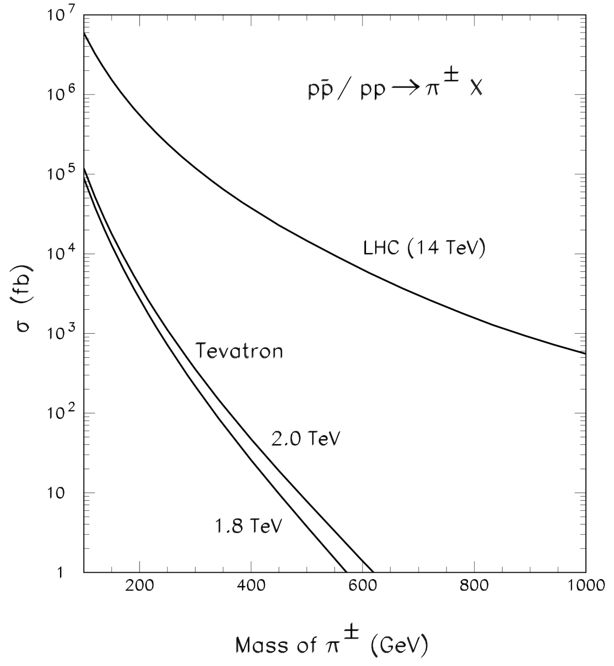


Topflavor: W' → t $\bar{b}$

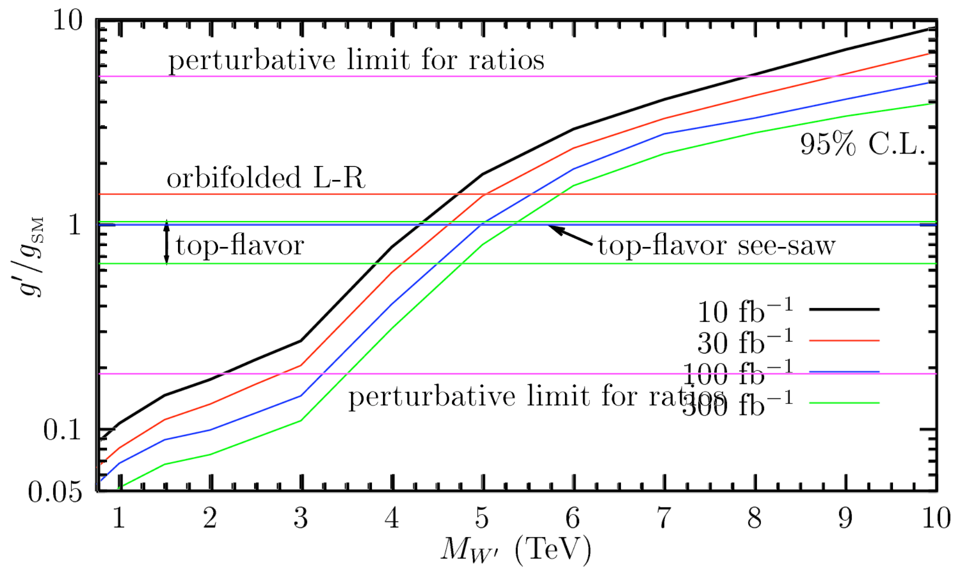
Simmons, PRD55, 5494 (1997)



He, Yuan PRL83,28 (1999)



Sullivan hep-ph/0306266

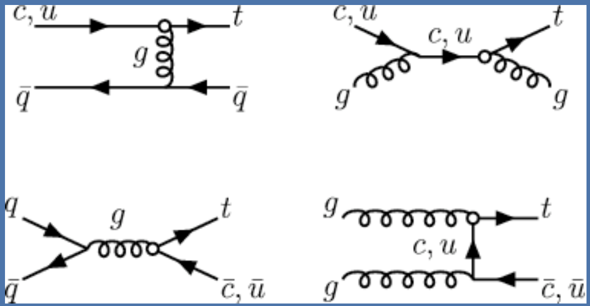


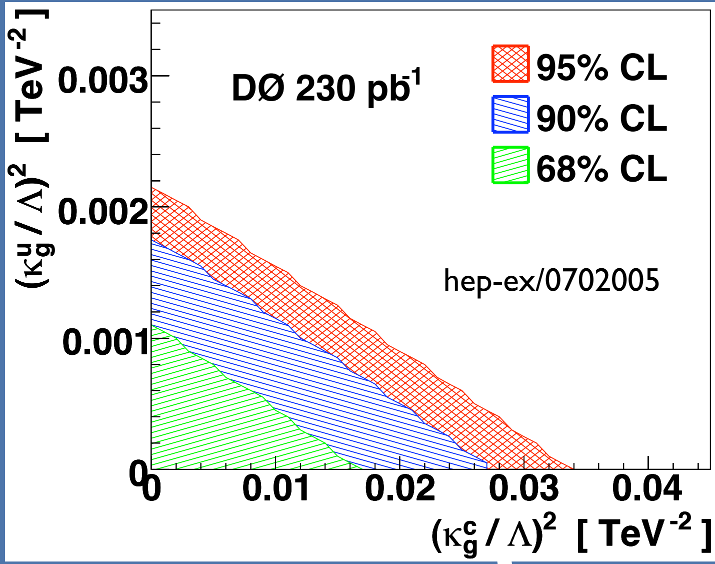
FCNC Production

- A FCNC interaction between the top and charm or up and the gluon can be bounded using single top production.

Malkawi, Tait PRD54, 5758 (1996)
Han, Hosch, Whisnant, Young, Zhang PRD58, 073008 (1998)

$$\frac{\lambda_g^c}{\Lambda^2}(H\bar{Q}_3)\sigma^{\mu\nu}F^a_{\mu\nu}c \rightarrow \frac{\kappa_g^c}{\Lambda}\bar{t}_L\sigma^{\mu\nu}F^a_{\mu\nu}c$$

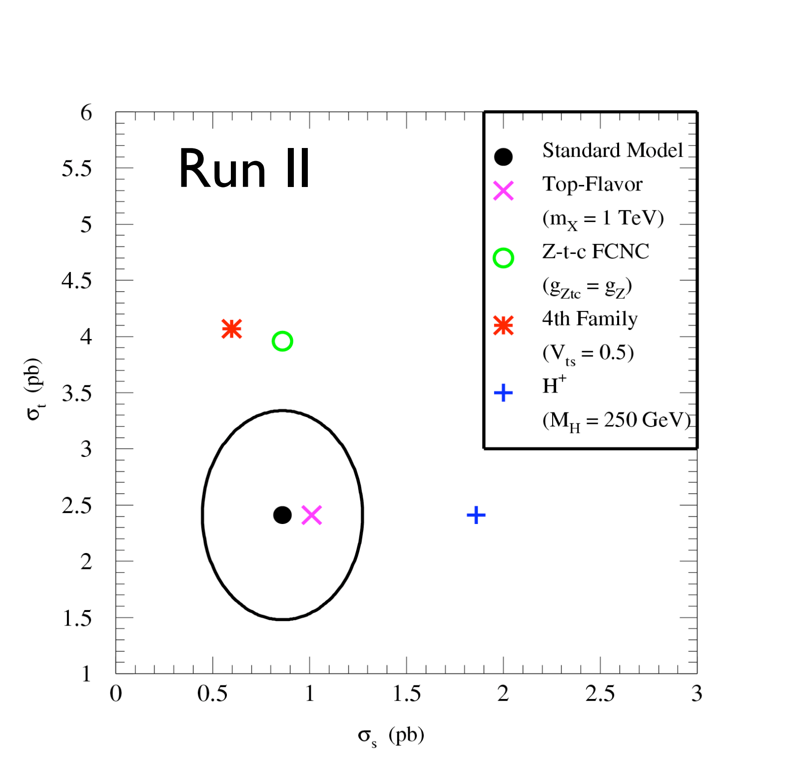


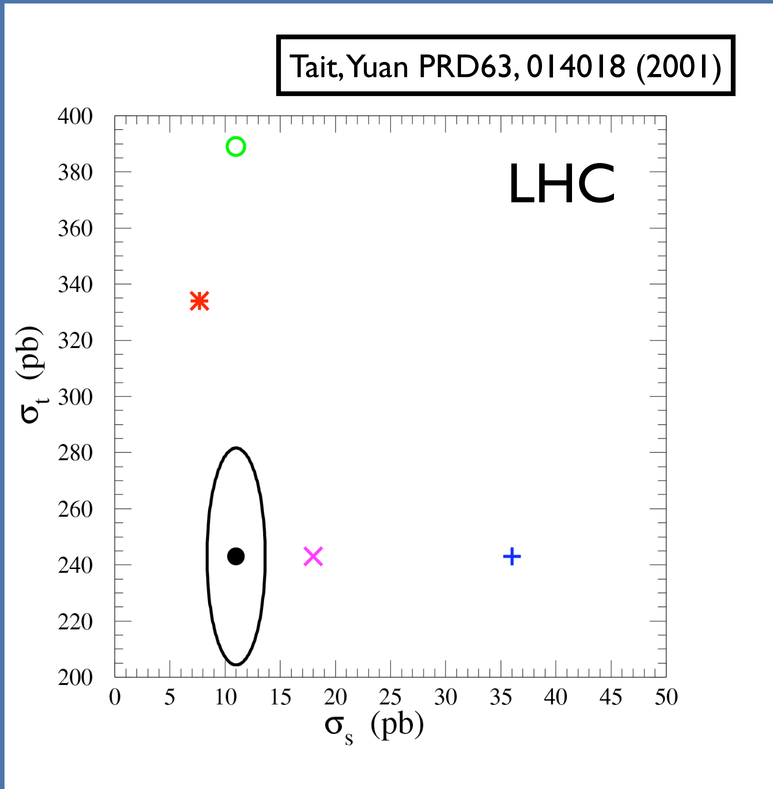


- Different operators can mediate interactions with the Z or photon, and can also induce rare top decays (whose BRs in the SM are too tiny even for LHC - they would be a clear sign of physics beyond the SM!).

σ_s-σ_t Plane

Since they are sensitive to different physics and have different, final states, σ_s and σ_t should be measured independently!





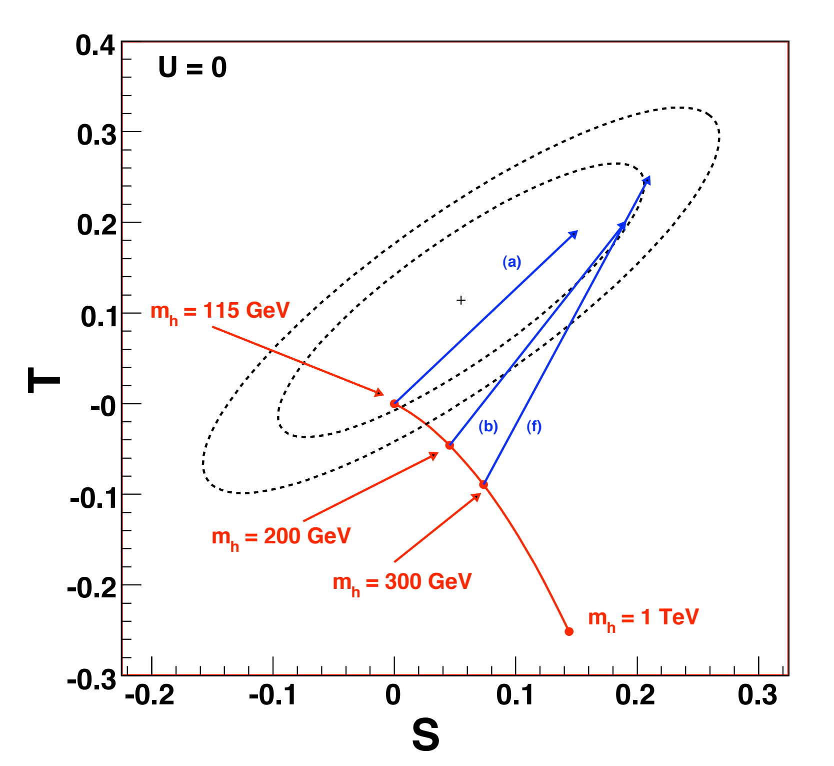
Theory + statistical errors only...

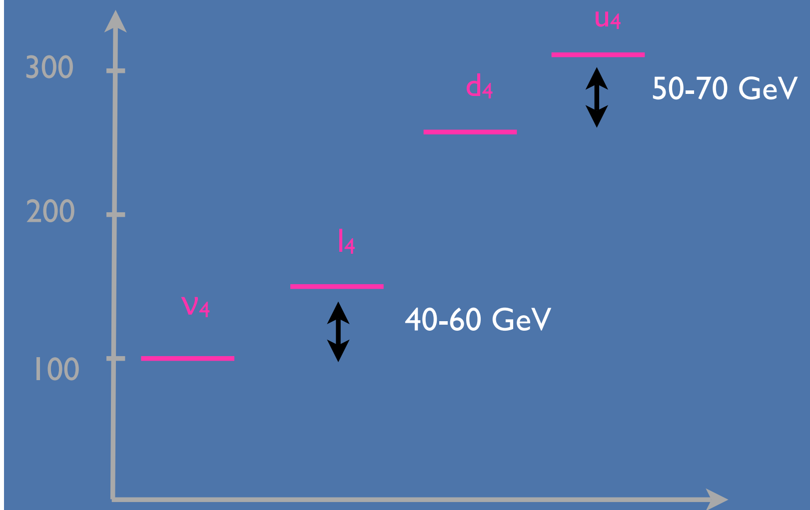
More Exotic Signatures

A 4th Generation??

"A 4th generation of ordinary fermions is excluded to 99.999% CL on the basis of the S parameter alone."

PDG 2006



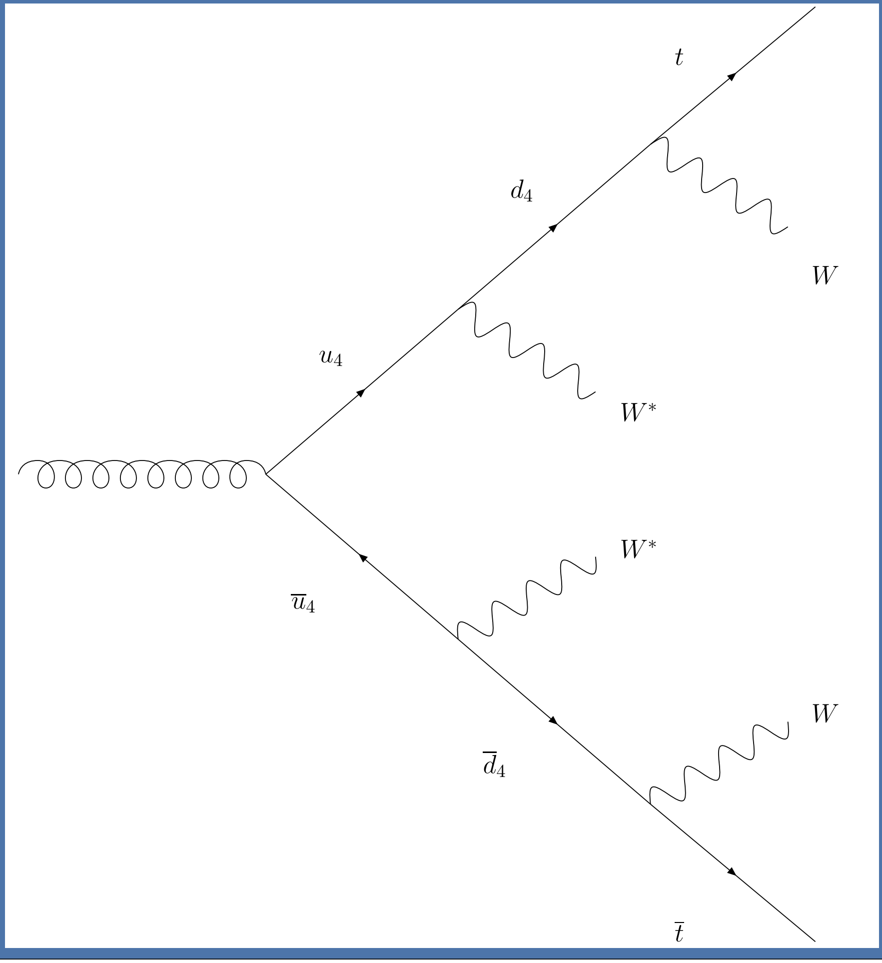


However, the PDG is not quite right...

Kribs, Plehn, Spannowsky, TT, hep-ph/0706.3718

Striking LHC Signals...

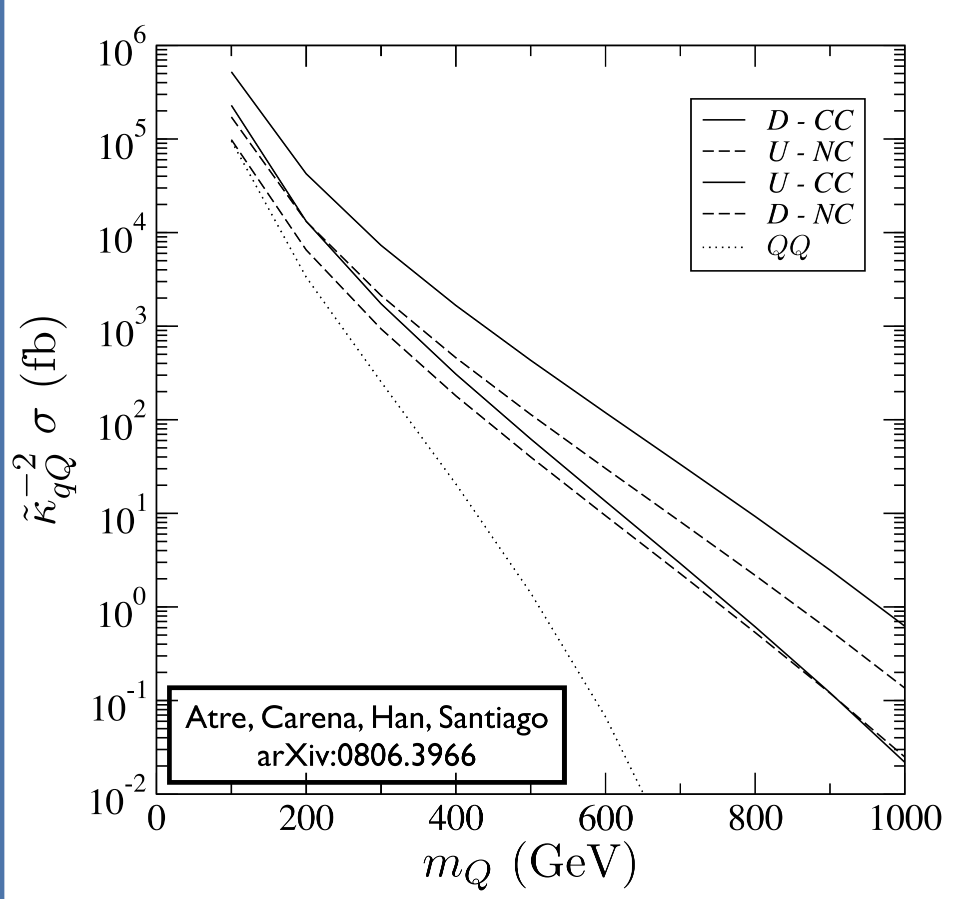
u_4 production:



Six W's and 2 b's!?!...
including two top quarks
a bewildering array of riches...

More Heavy Quarks

- Exotic heavy quarks which can decay through top are furnished by top-seesaw models, beautiful mirrors models, and as KK modes in warped extra dimensions.
- Typically such objects are heavier than chiral 4th generation ones.
- If heavy enough, the dominant production mechanism can be single production by electroweak interactions.

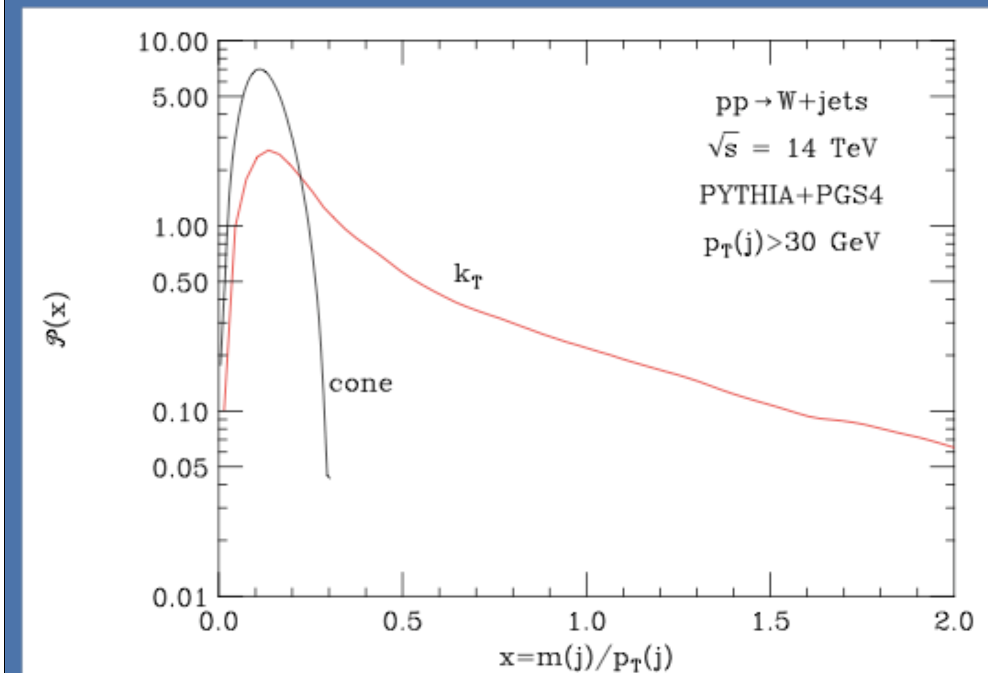


Conclusions

- 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.
  - Single top is a high background environment
- Top may be our portal to physics beyond the SM!

Bonus Material

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.

$$R = D = 0.5$$

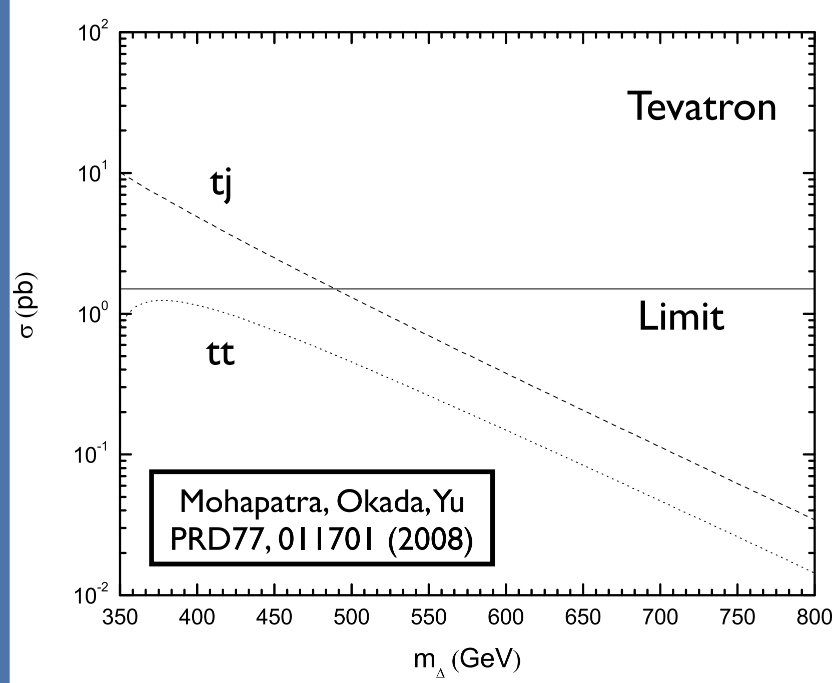
cone ↗ (R) ↖ k_T (D)

Baur, Orr, PRD76, 094012 (2007)

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



For work on reconstruction:
Han, Bai JHEP 0904:056 (2009)