Predictions from an Anomaly in the Top Quark Forward Backward Asymmetry

Jared Kaplan, SLAC
On 1101.5203 with Y. Bai, J. Hewett, T. Rizzo

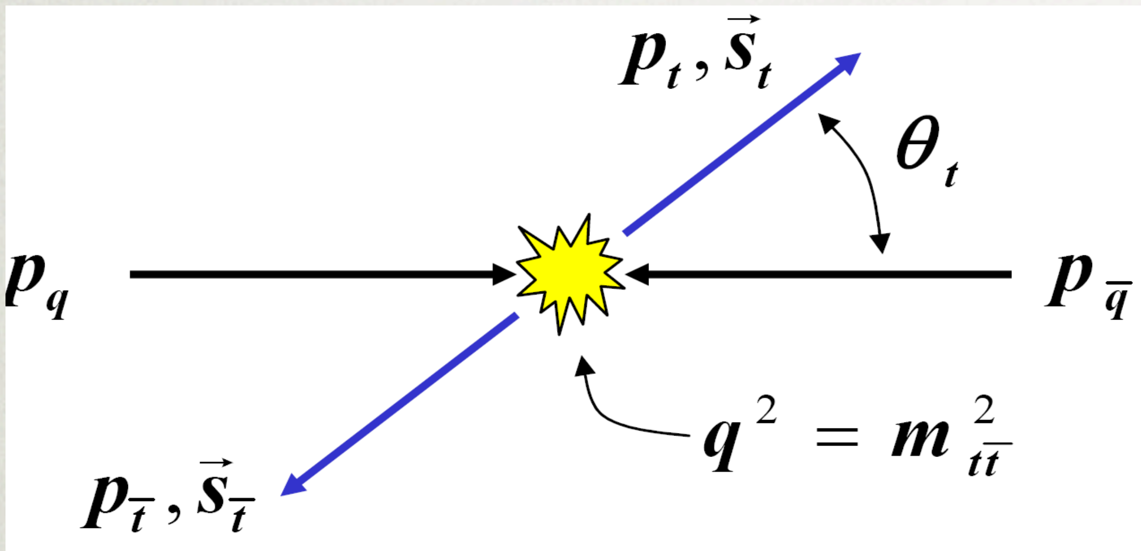
A Takeaway Point...

New Physics explanations of the FB Asymmetry are **already being tested** at the LHC.

Outline

- Evidence for and Characteristics of the Top Quark Forward-Backward Asymmetry
- Prerequisites for New Physics Models
- Axigluon from a General EFT
- Constraints from Dijets, the Top Production Cross Section, and Flavor
- LHC & Tevatron - Signatures & Follow-Ups
- Some Coset Models and Conclusions

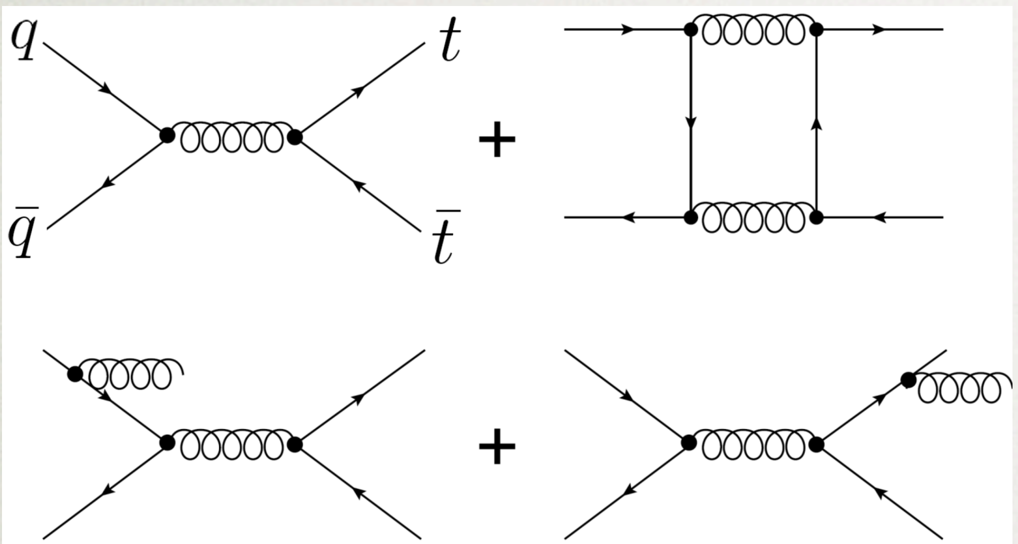
The F-B Asymmetry



$$A_{fb} = \frac{N_f - N_b}{N_f + N_b}$$

- Tevatron collides protons and ANTI-protons, breaking Charge and Parity
- Is this reflected in the final state?
- To analyze, need to measure sign of jets - use Tops
- Measurement (probably) impossible at LHC!

Standard Model Prediction



MC@NLO Predicts:

$$A_{fb}^{t\bar{t}} = 0.030 \pm 0.007$$

$$M_{t\bar{t}} > 450\,GeV$$

- LO diagram is symmetric
- largest NLO effect uses valence quark PDFs; smaller effect from qg initial state
- NLO diagrams "see" valence quark charges
- Virtual is Positive, Real Negative, so final result depends on the IR scale, ie minimum Jet Pt, but virtual > real

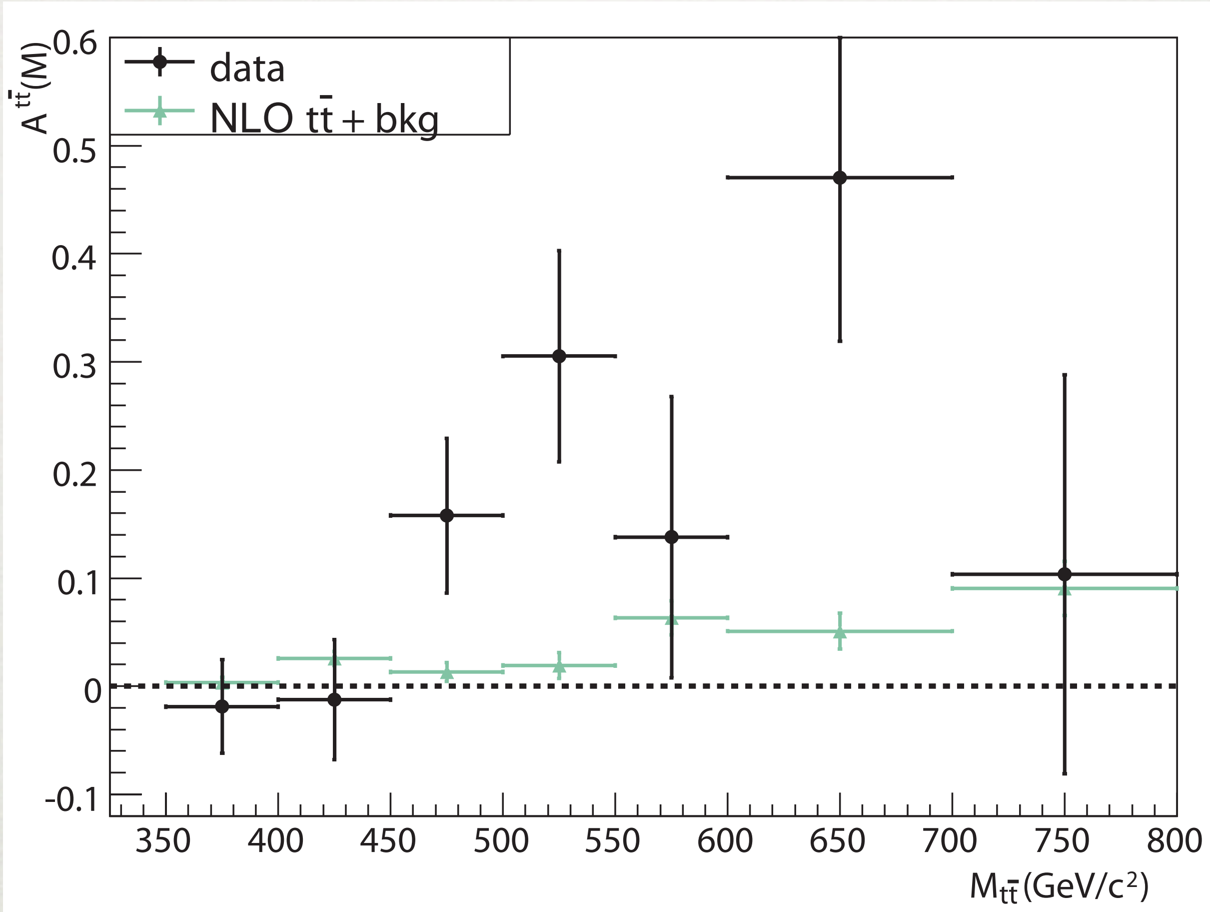
Old Evidence for an Asymmetry

- Old (0712.0851) D0 Measurement of $A_{fb}^{t\bar{t}} = 0.12 \pm 0.09$ with $0.9\, fb^{-1}$
- Old (0806.2472) CDF Measurement of $A_{fb}^{t\bar{t}} = 0.24 \pm 0.14$ with $1.9\, fb^{-1}$

new Evidence for an Asymmetry

- New (1101.0034) CDF Measurement of $A_{fb}^{t\bar{t}} = 0.475 \pm 0.114$ with $5.3 fb^{-1}$ for $M_{t\bar{t}} > 450\, GeV$
- New CDF Conference note analyzing dilepton channel, finding asymmetry of $A_{fb}^{t\bar{t}} = 0.21 \pm 0.09$ with 334 events
- Parton level asymmetries of 40%!!

The New CDF Data



- Requires 1 lepton, 4 jets, 1 b-jet, and top reconstruction
- Total of 1260 events after selection
- directionality from hadronic top, sign from lepton

Energy Dependence

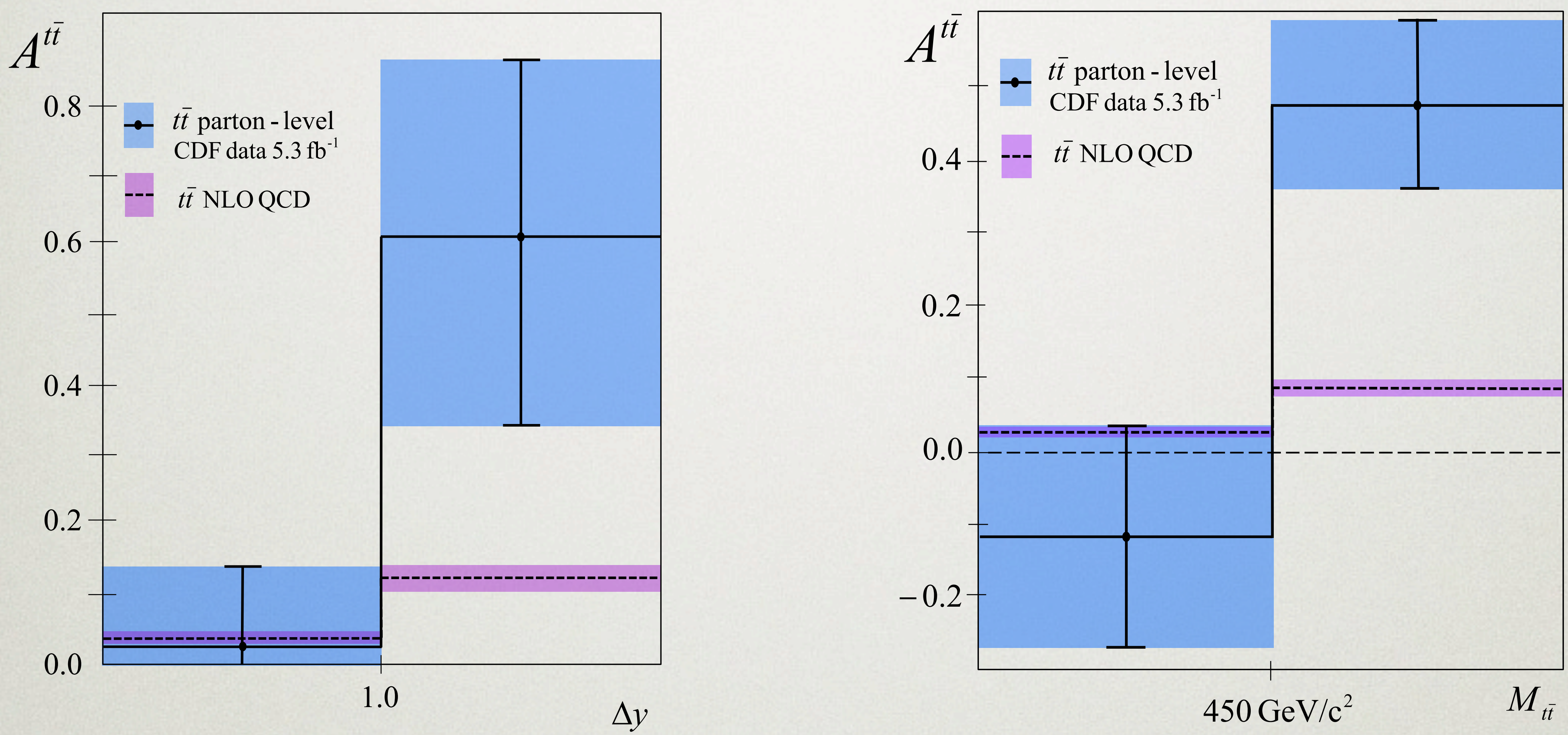
- To get best statistics for energy dependence, looked at Axigluon-type models and found best division
- Found 450 GeV, so binned data as low and high energy with this cut

New CDF Data

selection	N events	all $M_{t\bar{t}}$	$M_{t\bar{t}} < 450$ GeV/c^2	$M_{t\bar{t}} \geq 450$ GeV/c^2
standard	1260	0.057±0.028	-0.016±0.034	0.212±0.049
electrons	735	0.026±0.037	-0.020±0.045	0.120±0.063
muons	525	0.105±0.043	-0.012±0.054	0.348±0.080
data $\chi^2 < 3.0$	338	0.030±0.054	-0.033 ± 0.065	0.180 ± 0.099
data no-b-fit	1260	0.062±0.028	0.006 ± 0.034	0.190 ± 0.050
data single b-tag	979	0.058±0.031	-0.015±0.038	0.224±0.056
data double b-tag	281	0.053±0.059	-0.023±0.076	0.178±0.095

- $\chi^2 < 3.0$ requires better top reconstruction
- no-b-fit ignores knowledge of b-jets when reconstructing

Unfolded CDF Data



- CDF Unfolded detector effects to give 4 bins
- the dominant systematics are from background magnitude and the physics model (showering, PDFs, etc)

Model Prerequisites

- Asymmetry is LARGE
- Thus expect new physics gives asymmetry from interference with QCD
- Interference requires Tops to be in a Color Octet, Vector state since these are the quantum numbers of a gluon

Model Prerequisites

- t-channel contribution produces like sign tops, requires baroque flavor models...
- s-channel requires a new heavy color octet vector boson, "Axigluon"
- couples to dijets of all generations

Axigluon from a General EFT

- EFT with a general Color Octet Vector
- Axial and Vector Couplings to Light Quarks and to Top/Bottom, separately
- Mass and Width as Parameters, expect:

$$\Gamma(G') = \frac{\alpha_s\, M_{G'}}{6}\left[4(|g_V^q|^2 + |g_A^q|^2) + 2(|g_V^t|^2 + |g_A^t|^2)\right]$$

Axigluon from a General EFT

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta^*} = \alpha_s^2\frac{\pi\sqrt{1-4m^2}}{9\hat{s}}\Bigg[\left(1+4m^2+C(\theta^*)^2\right)\left(1-\frac{2g_V^q g_V^t\,\hat{s}(M_{G'}^2-\hat{s})}{(\hat{s}-M_{G'}^2)^2+M_{G'}^2\Gamma_G^2}+\frac{g_V^{t\,2}(g_V^{q\,2}+g_A^{q\,2})\hat{s}^2}{(\hat{s}-M_{G'}^2)^2+M_{G'}^2\Gamma_G^2}\right)$$
$$+\left(1-4m^2+C(\theta^*)^2\right)g_A^{t\,2}(g_V^{q\,2}+g_A^{q\,2})\frac{\hat{s}^2}{(\hat{s}-M_{G'}^2)^2+M_{G'}^2\Gamma_G^2}$$
$$-4g_A^q g_A^t C(\theta^*)\left(\frac{\hat{s}(M_{G'}^2-\hat{s})}{(\hat{s}-M_{G'}^2)^2+M_{G'}^2\Gamma_G^2}-2g_V^q g_V^t\frac{\hat{s}^2}{(\hat{s}-M_{G'}^2)^2+M_{G'}^2\Gamma_G^2}\right)\Bigg] \quad (1)$$

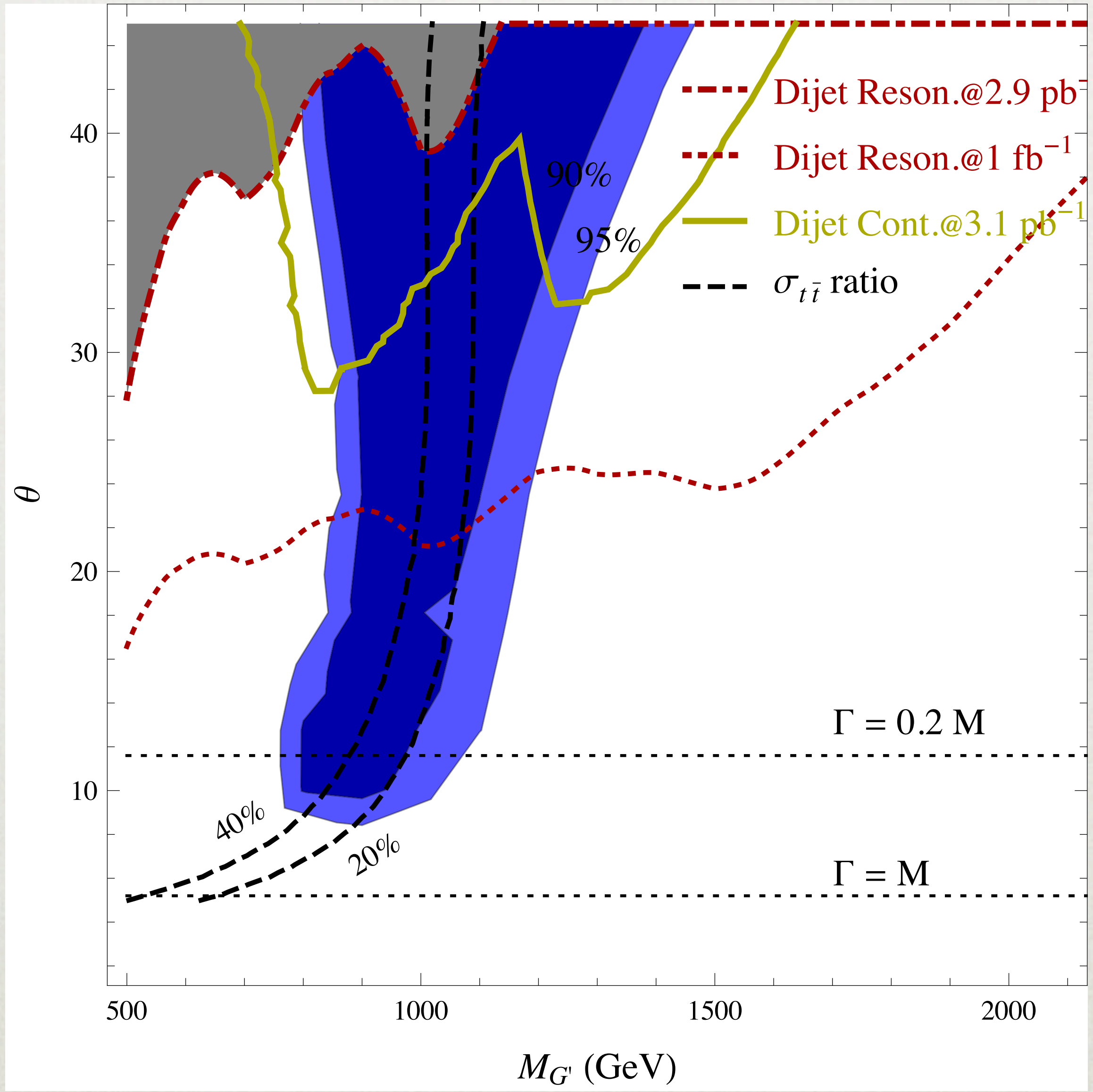
Why put such a complicated equation in a talk!?

- Asymmetry proportional to $-g_A^q g_A^t$
- Asymmetric term grows with $M_{t\bar{t}}^2$ relative to QCD
- total $t\bar{t}$ cross section decreases with $g_V^t g_V^q$

Constraints

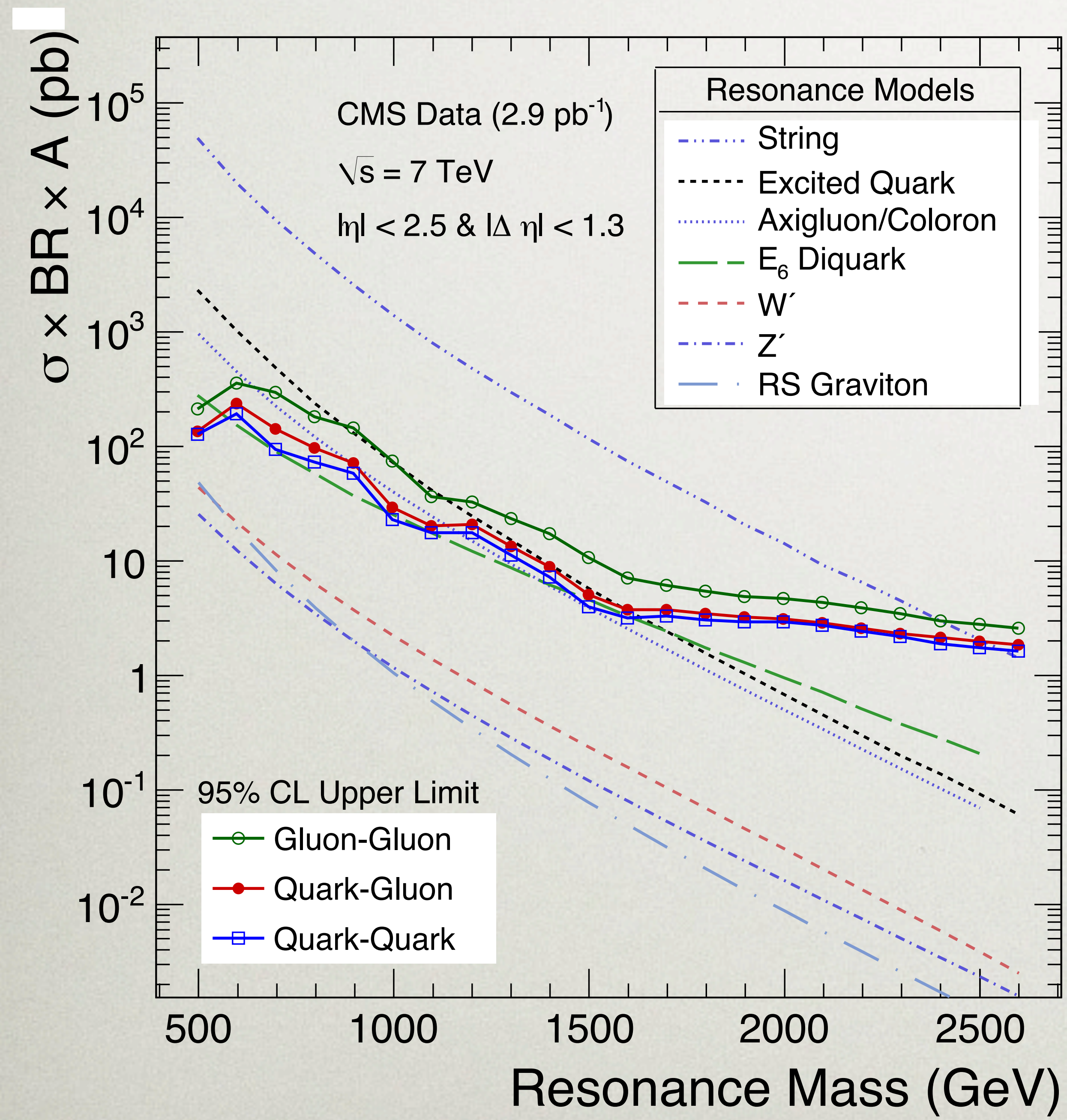
- Flavor Effects Mediated by Axigluon
- Top Quark Total Cross Section and Mass Dependent Cross Section
- Dijet Resonance and Contact Operator Searches - LHC Dominated, Already!

A Preview of Results



Fits to Unfolded Parton-Level Data

Dijet Resonance Searches at the LHC!



1010.0203, CMS

- based on 2.9 pb^-1
- for Axigluon, only involves couplings to light quarks
- rescale results for different couplings

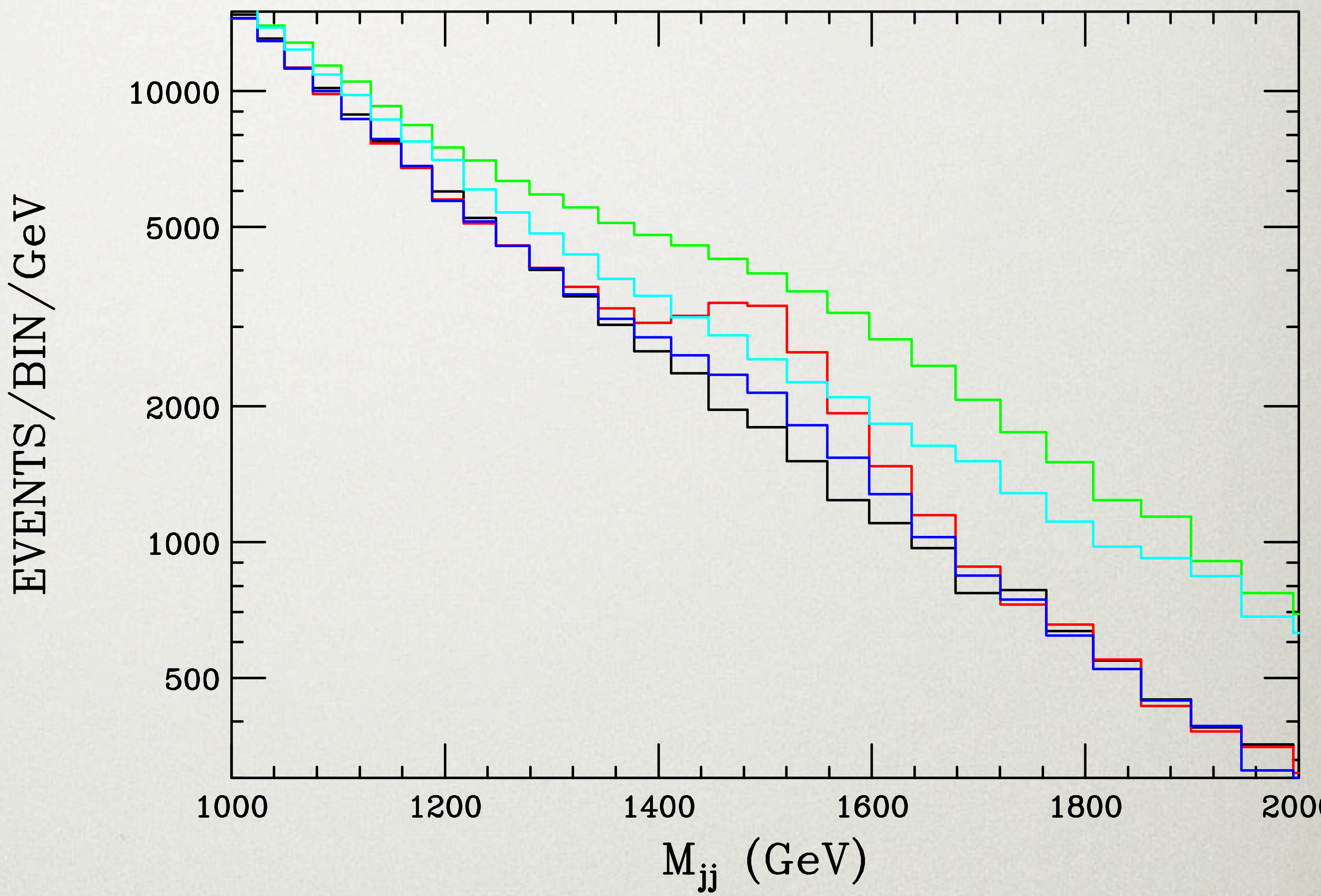
Rescale from CMS

$$\frac{\sigma \times BR(q\bar{q} \to G' \to jj)}{\sigma \times BR(\text{coloron})} = \frac{6}{5}\left(|g_V^q|^2 + |g_A^q|^2\right) \frac{4(|g_V^q|^2 + |g_A^q|^2) + (|g_V^t|^2 + |g_A^t|^2)}{4(|g_V^q|^2 + |g_A^q|^2) + 2(|g_V^t|^2 + |g_A^t|^2)},$$

- Colorons have couplings = 1 for us
- Limits will rapidly improve this year, at least as Luminosity^(1/2)
- Eventually will have TTbar resonance, but probably not competitive this year
- but is it a "resonance"?

Resonance or Shoulder?

Width/Mass
= 0.1, 0.2, 0.4, 0.8

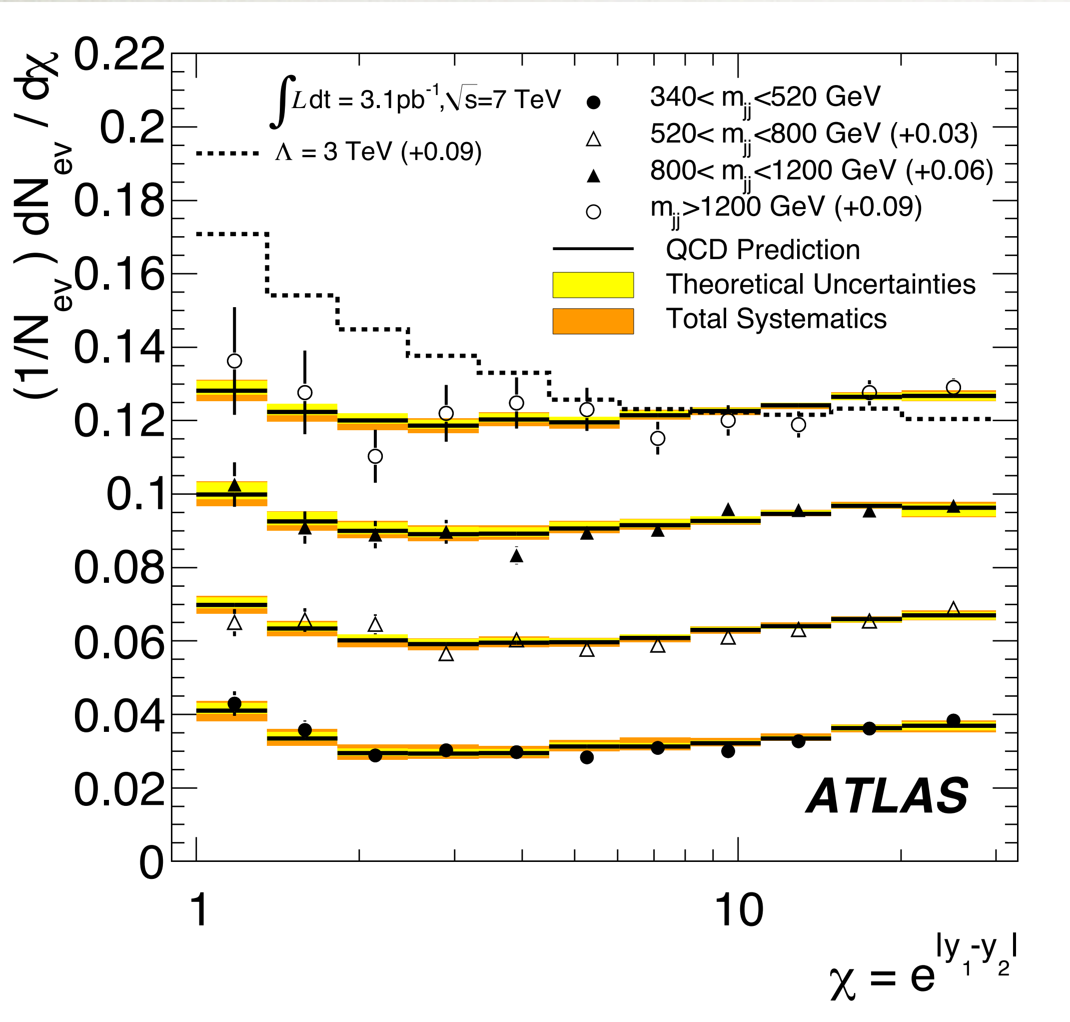


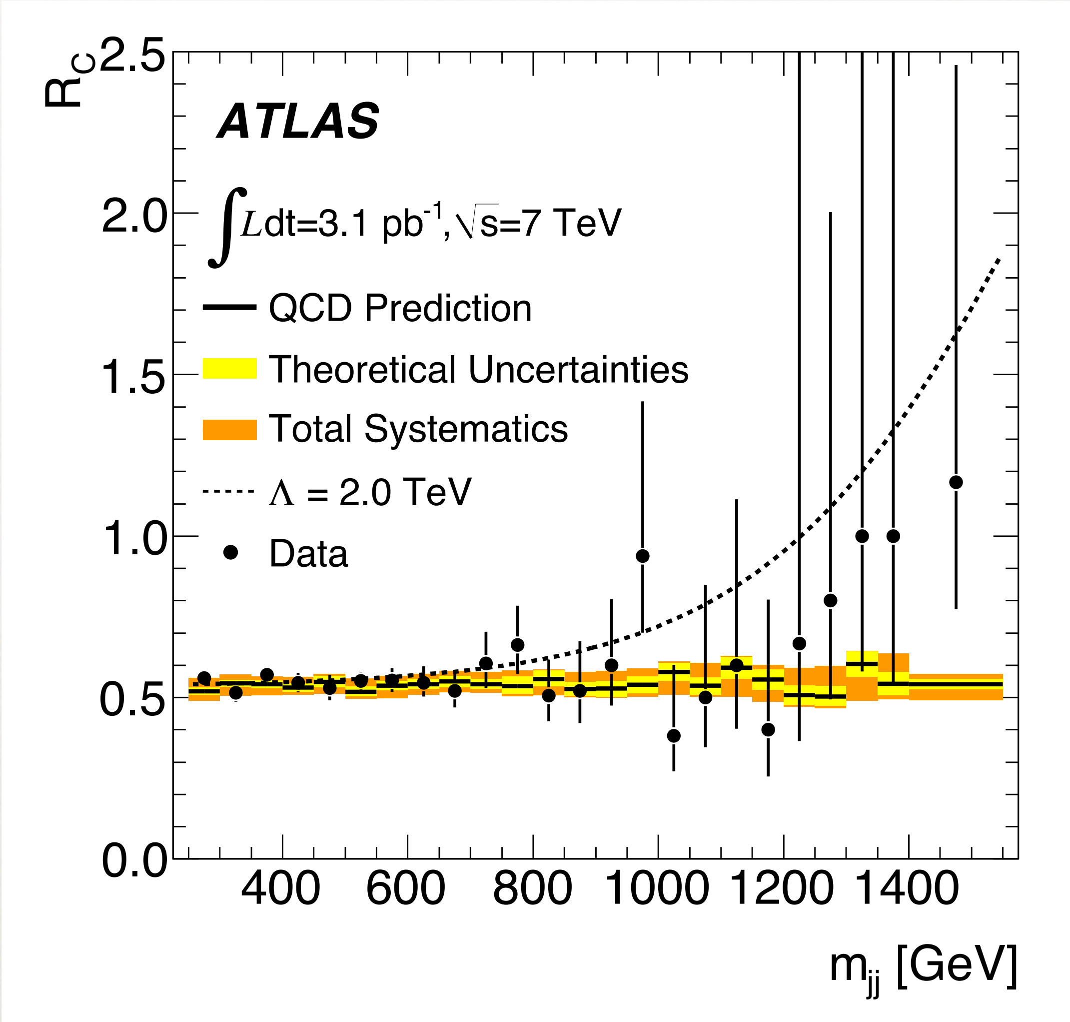
1.5 TeV Axigluon with QCD couplings
Can constrain via Contact Interaction Searches...

Physics of Contact Operator Searches

- Most QCD dijet production comes from t-channel gluons
- Dijets have flat distribution in rapidity
- New contributions to jet cross section dominated at small rapidity
- We can constrain 4 fermion operators using rapidity plots...

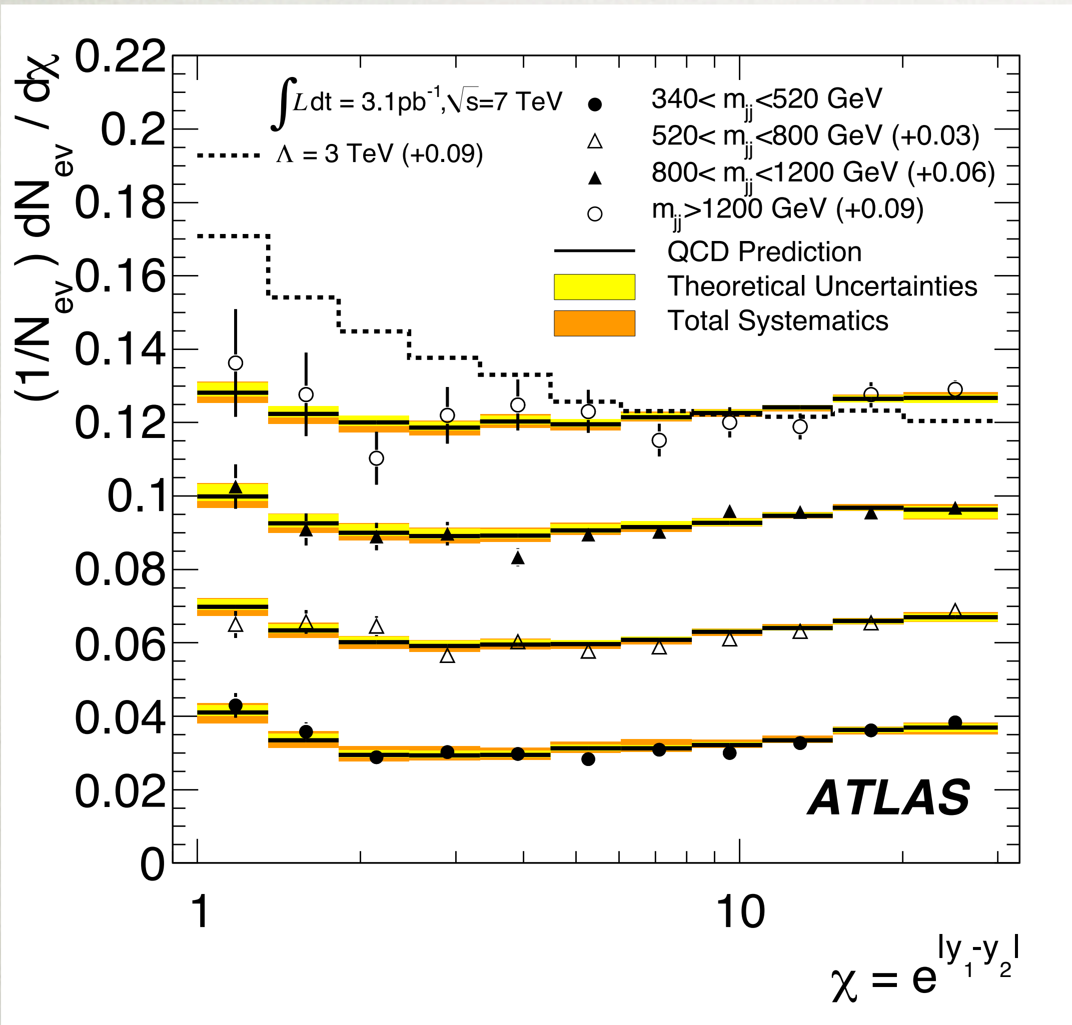
Contact Operator Searches





1009.5069 ATLAS

Constraints from Contact Operator Searches



- Use first 4 bins
- 800 to 1200 GeV and > 1200 GeV data (gives structure to curves on plots)

Contact Ops Most Stringent Constraint

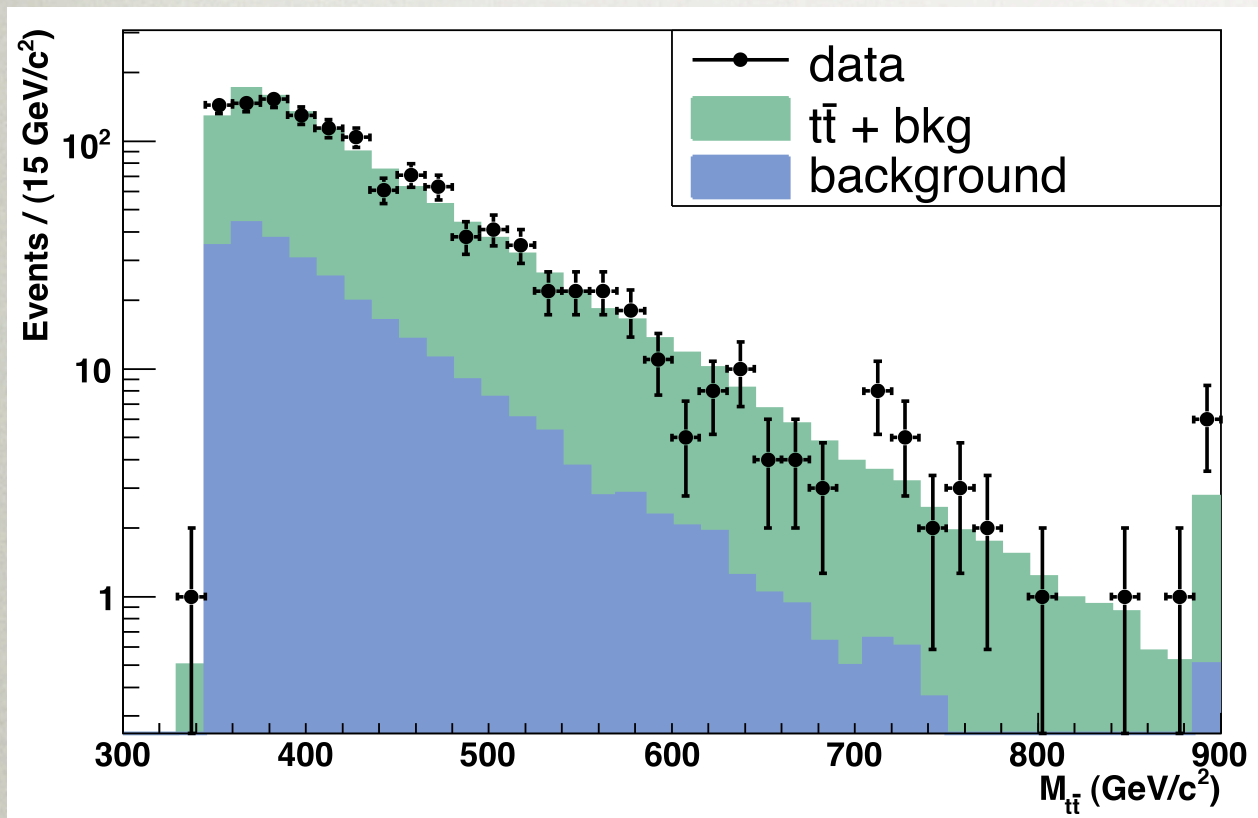
Currently, contact operator searches provide more stringent constraints than dijet resonance searches because they allow background subtraction, but they have larger systematics, so with more data, resonance searches will eventually dominate.

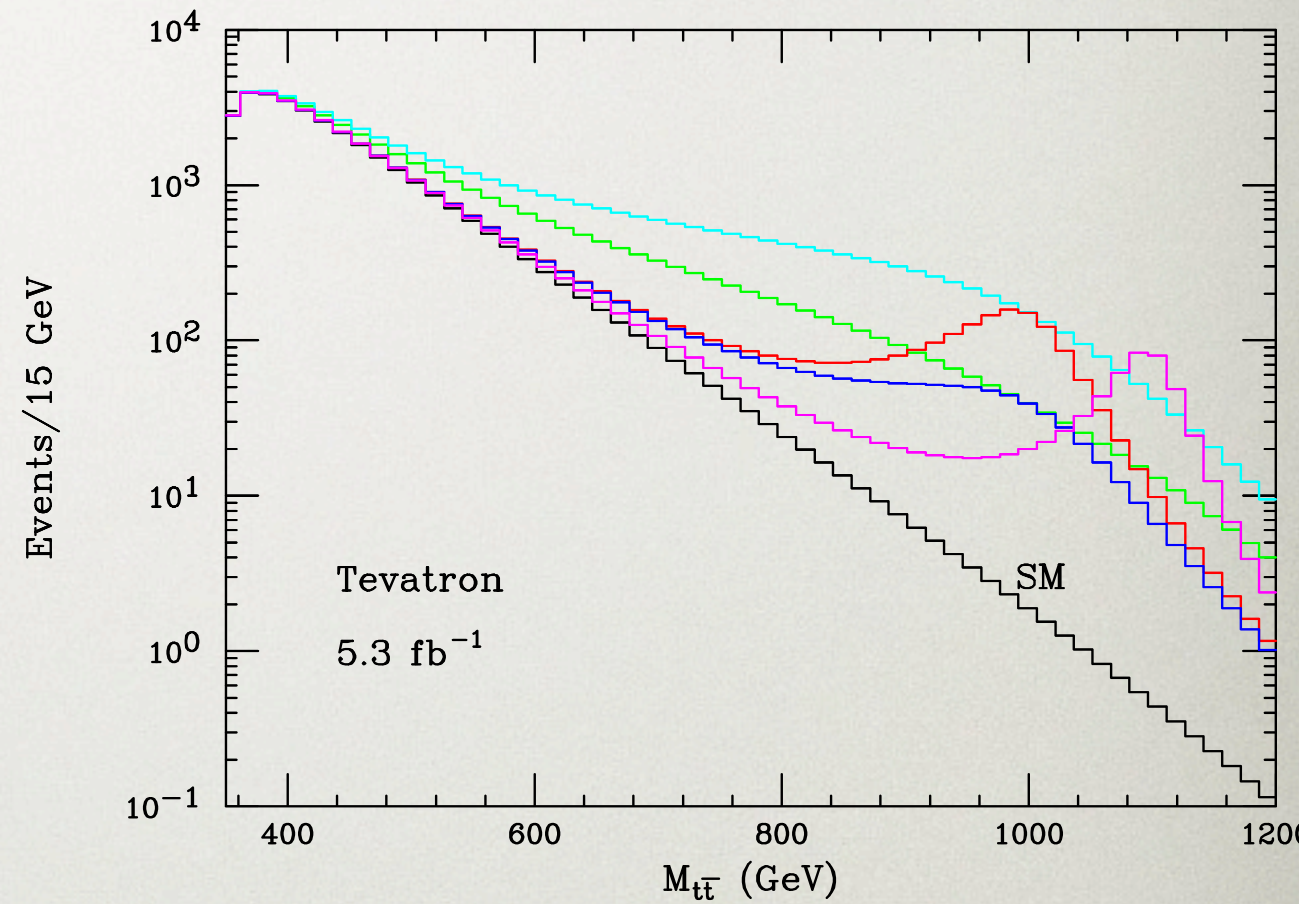
Improving non-resonance search is important at higher energies!

Top Cross Section

- TTbar Cross Section Predicted at NLO, measured at Tevatron to within ~10%
- Axigluon modifies total and shape, so there should be constraints...
- But no TTbar resonance search above 800 GeV, so limits are unclear
- Compromise - we display 20% and 40% axigluon contribution to Mtt > 450 GeV

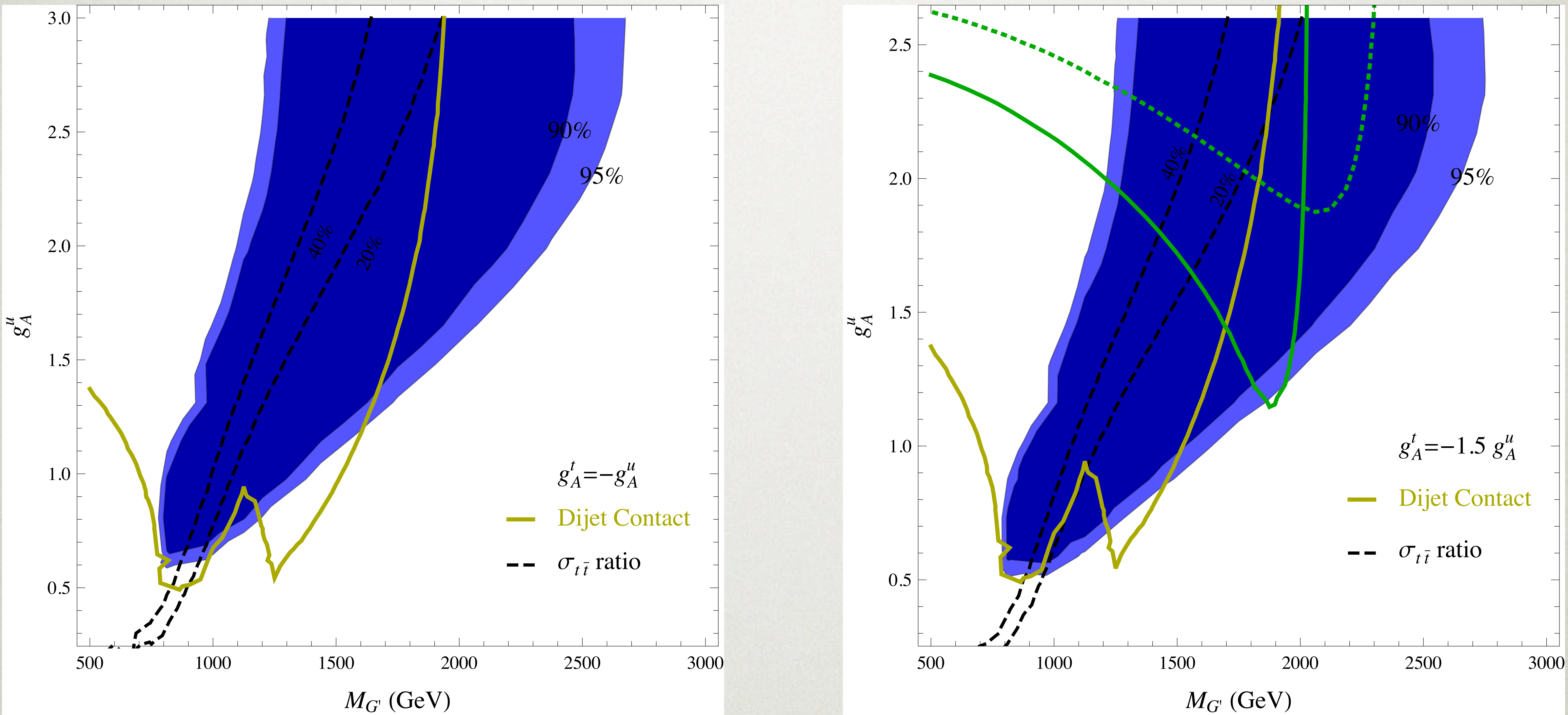
CDF Data For Top Production





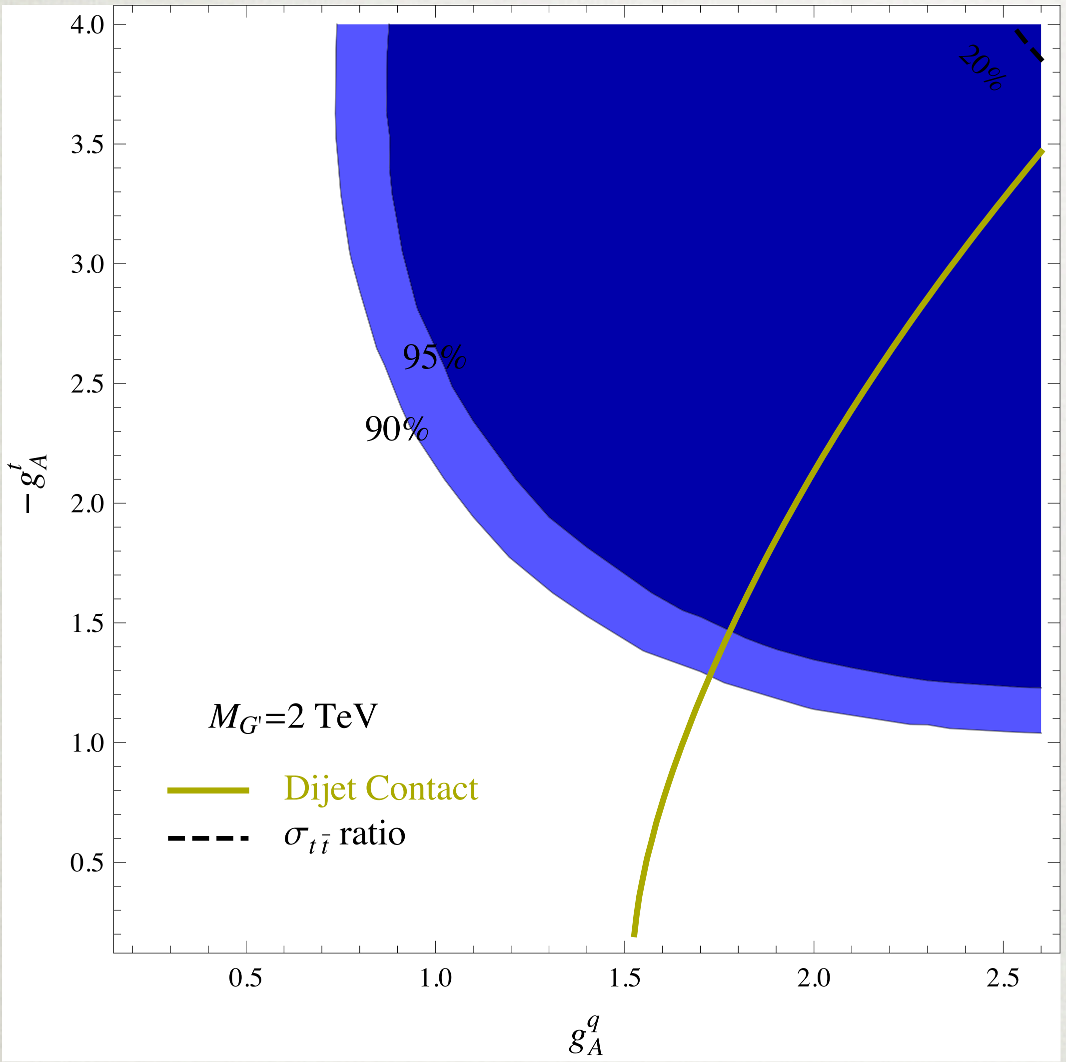
Width/Mass = 0.1, 0.2, 0.4, 0.8

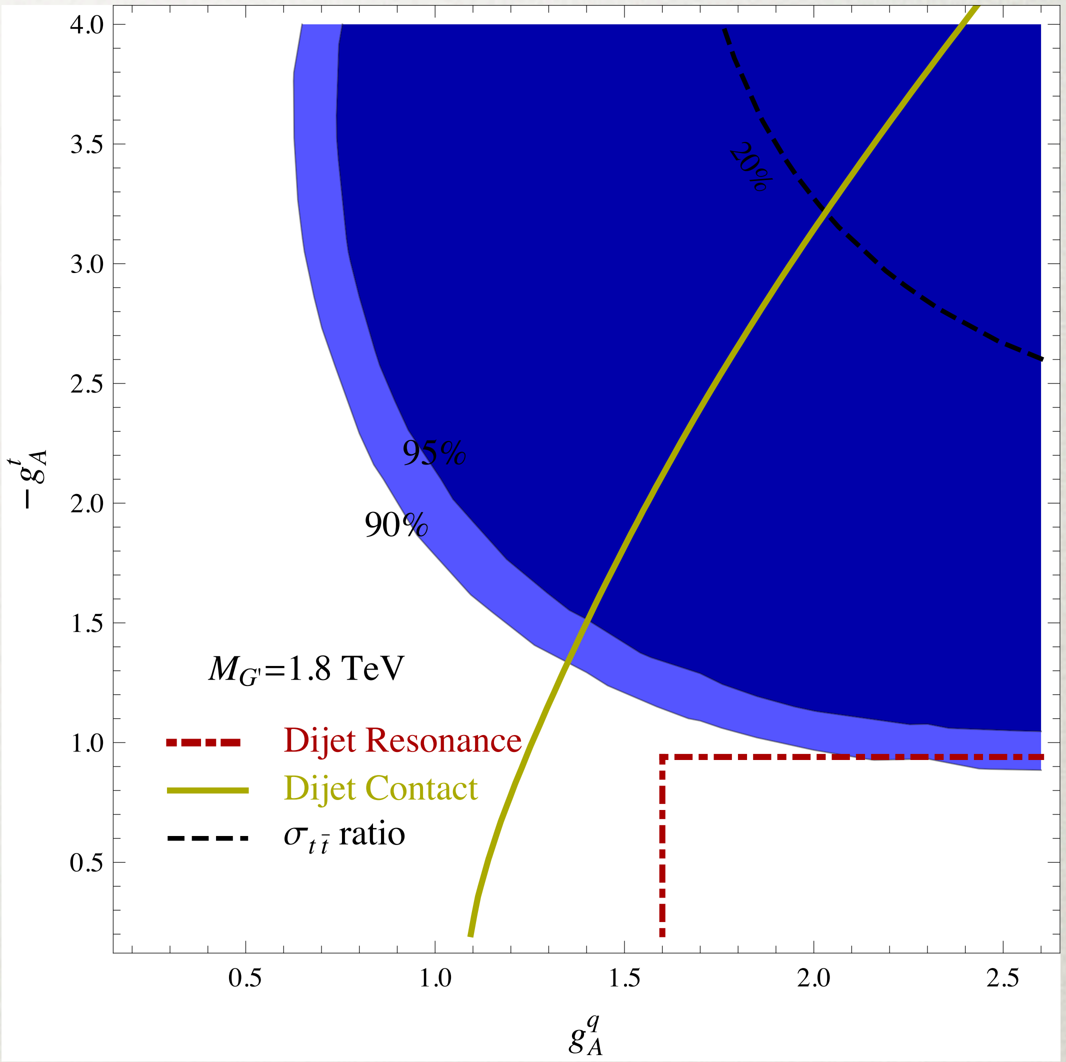
Effective Field Theory Parameter Space



Fits to Unfolded Parton-Level Data

Effective Field Theory Parameter Space





Flavor Constraints

- Axigluon couples differently to third vs first two generations
- thus mediates flavor violating processes
- very (flavor) model dependent, so we will examine a few possibilities
- B-mixing, D-mixing, Kaon system...

Flavor Constraints

Example - coupling of b′s to other generations:

$$\mathcal{L}_{\rm FCNC} = -g_s \bar{b}\, t^a \gamma^\mu (C^D_{L,3q}\, P_L + C^D_{R,3q}\, P_R) q\, G'^{\mu}_a + h.c.$$

Governed by mixing matrix

$$C^D_{L,kj} = (a_3 - a_1)_L (U^D_L)_{k3} (U^{D\,\dagger}_L)_{3j}$$

where a_i are couplings to ith generation
and U^D_L are left, down-type mixing matrices

Flavor Operators

Match onto a Hamiltonian and RG evolve:

$$\mathcal{H}_{\Delta B=2} = \frac{2\pi\alpha_s}{3M_{G'}^2}\Big[(C^D_{L,3q})^2 Q_{1L} + (C^D_{R,3q})^2 Q_{1R} - C^D_{L,3q}C^D_R Q_2 - 6\, C^D_{L,3q}C^D_{R,3q} Q_3\Big]$$

Use constraints on these operators choose flavor model for mixing matrices:

(α)

$$U_L^D = U_R^D = U^D$$

$$U_L^U = U_R^U = U^U$$

(β)

$$U_R^U = U_R^D = \mathbb{I}_3$$

Flavor Summary

	Lower bound on $M_{G'}$ in TeV	
	(α)	(β)
Kaon System	$5000 \times \lvert U^D_{23}\, U^D_{13}{}^* \rvert$	$500 \times \lvert U^D_{23}\, U^D_{13}{}^* \rvert$
B Mixing	$500 \times \lvert U^D_{33}\, U^D_{13}{}^* \rvert$	$100 \times \lvert U^D_{33}\, U^D_{13}{}^* \rvert$
D Mixing	$4500 \times \lvert U^U_{23}\, U^U_{13}{}^* \rvert$	$600 \times \lvert U^U_{23}\, U^U_{13}{}^* \rvert$

Constraints on mixings from K, B, and D, assuming no new complex phases affecting the Kaon system.

Flavor Constraints

All we know for sure is that:

$$V_{CKM} = U_L^U U_L^{D\,\dagger}$$

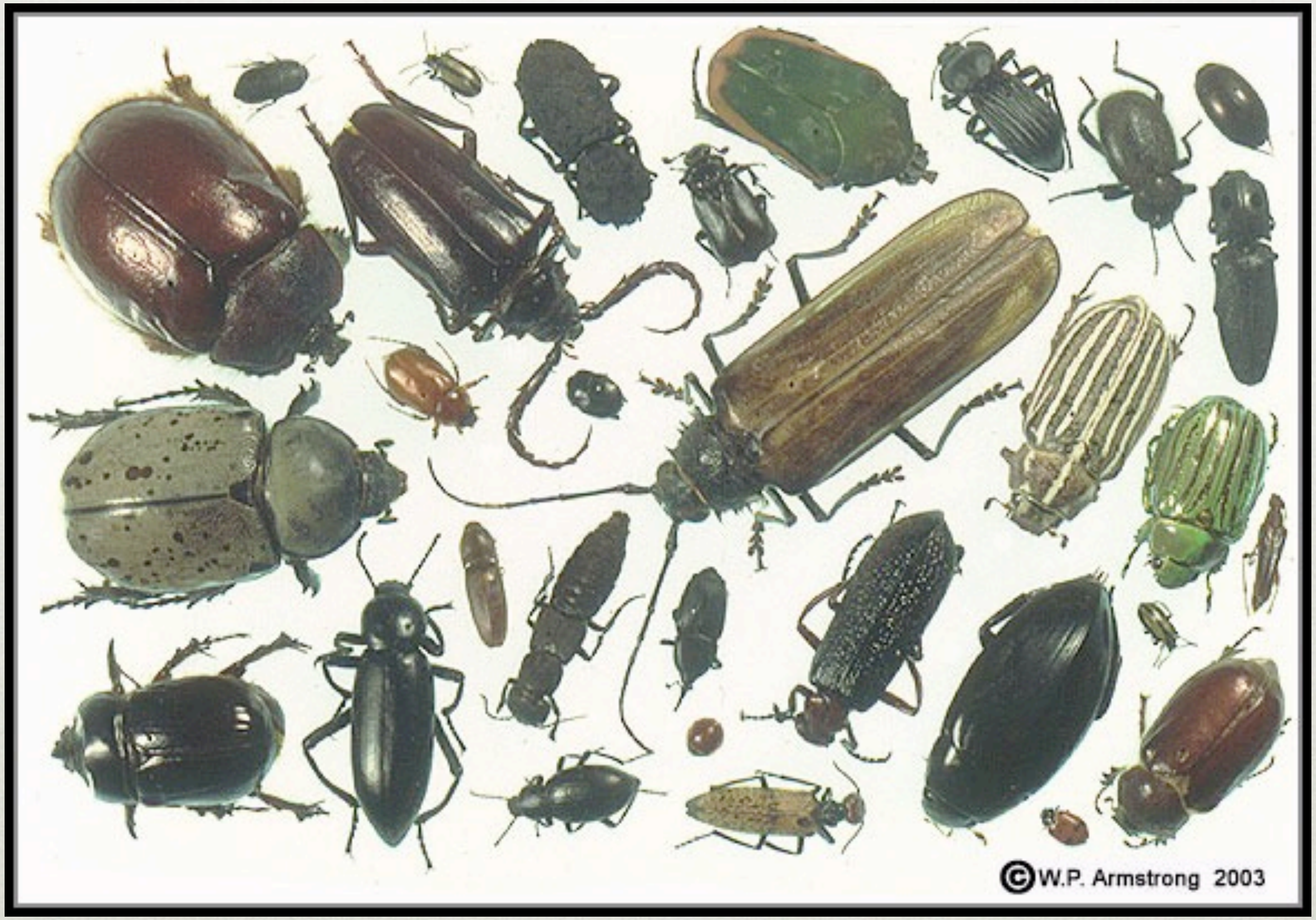
If we push all mixings into down sector, find:

$$(\alpha) \qquad M_{G'} \gtrsim 1.6|g_A^t - g_A^q| \text{ TeV}$$

$$(\beta) \qquad M_{G'} \gtrsim 200|g_A^t - g_A^q| \text{ GeV}$$

So generically, there are significant flavor constraints, but they can be evaded in natural models.

Specific Models



Specific Coset Models

A natural EFT for an Axigluon is a coset such as

$$SU_L(3) \times SU_R(3)/SU(3)$$

Must assign 3rd generation L & R opposite to that of the first two generations to generate the correct sign for the Axigluon couplings.

Simplest 2-Site Model

Choose couplings and mixing angle so that

$$g_s = h_1 \cos\theta = h_2 \sin\theta$$

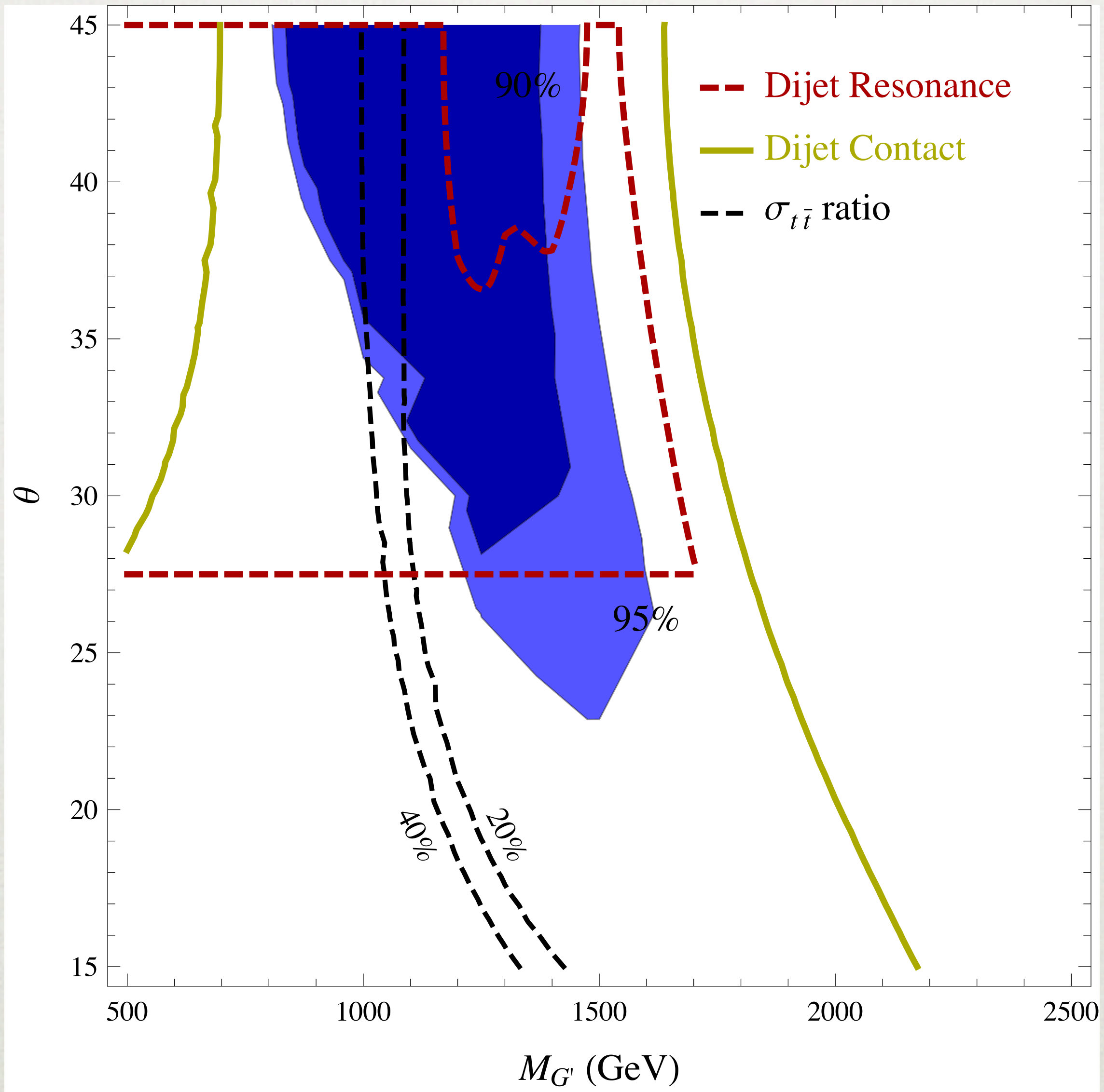
The gluon and Axigluon fields are simply

$$G^\mu = \cos\theta\, G_1^\mu + \sin\theta\, G_2^\mu$$

$$G'^{\,\mu} = -\sin\theta\, G_1^\mu + \cos\theta\, G_2^\mu$$

Essential point: 3rd Gen. vs Light Quarks given opposite site assignments.

The Simplest 2-Site Coset Model



(is ruled out)

What Went Wrong?

- Couplings too small overall, forcing us to have a light-ish Axigluon
- Not enough freedom to couple the Axigluon differently to the 3rd generation vs the light quarks

More Involved Models...

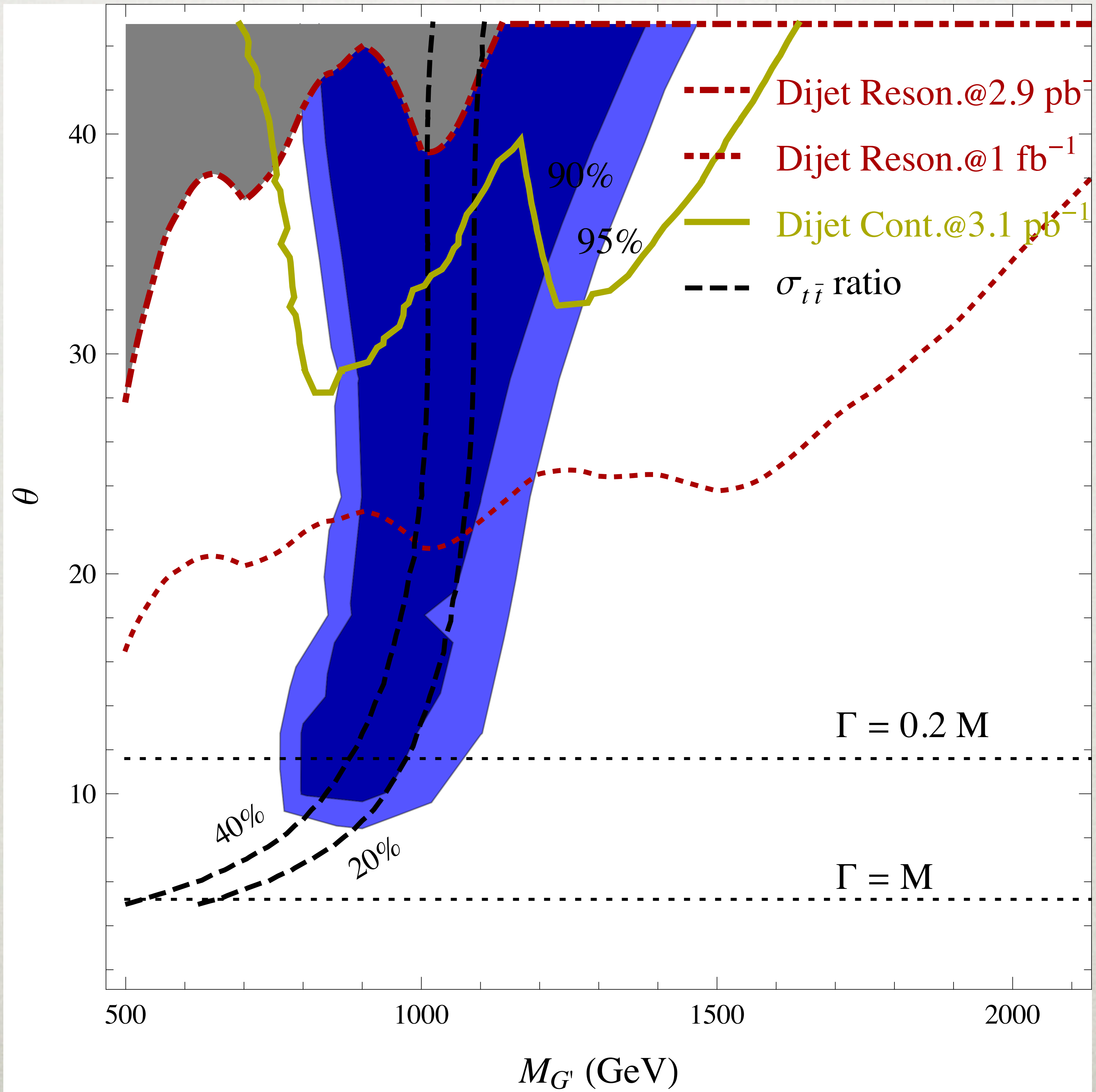
- Can add 3rd site, but no improvement
- However, adding a vector-like fermion mixing with light quarks helps...

$$
\begin{aligned}
u_R^{(m)} &= \cos\alpha\, u_R^{(f)} + \sin\alpha\, \psi_R^{(f)}\,, \\
\psi_R^{(m)} &= -\sin\alpha\, u_R^{(f)} + \cos\alpha\, \psi_R^{(f)}
\end{aligned}
$$

We suppress all vector-like couplings with

$$\sin\alpha = \sqrt{2}\sin\theta$$

Add a Vector-like Fermion to The Mix...



An Example of a Model Prediction

Selection	$M_{t\bar{t}} < 450$ GeV	$M_{t\bar{t}} > 450$ GeV
Parton Level Exp. Data	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
Model Prediction	0.06	0.21

Selection	$\|\Delta y\| < 1.0$	$\|\Delta y\| > 1.0$
Parton Level Exp. Data	$0.026 \pm 0.104 \pm 0.056$	$0.611 \pm 0.210 \pm 0.147$
Model Prediction	0.08	0.27

From 2-site model with vector-like fermion and Axigluon at 1.1 TeV

Model Difficulties

- Getting large axial couplings with small new vector couplings is challenging
- Results in weakly coupled models with light Axigluons - very constrained
- So: the most plausible "model" is probably a heavy (2 TeV) strongly coupled Axigluon

Experimental Signatures and Follow-Ups

LHC Signatures: Dijets

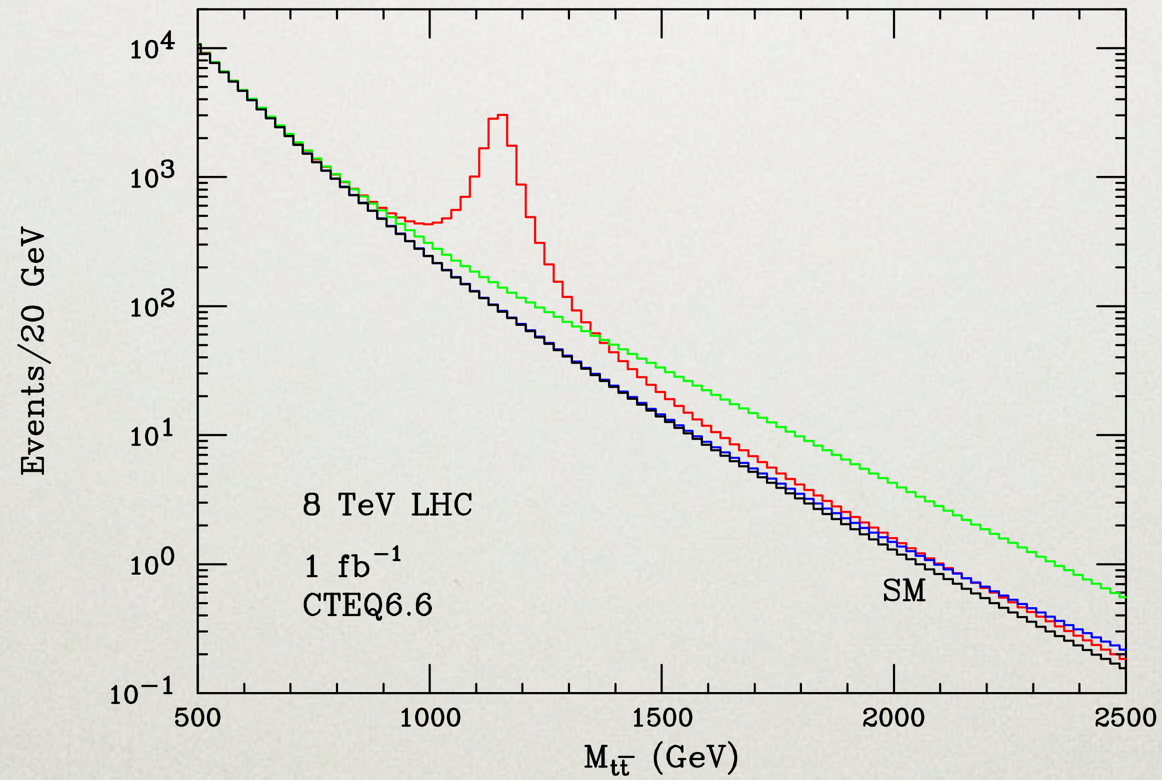
- Depending on couplings, could see a Dijet resonance
- Otherwise use shapes of distributions; for an Axigluon with:

$$M_{G'} = 2\ \text{TeV},\ g_A^u = 1.5,\ g_A^t = -2$$

One could exclude at 95% with ~45 pb^-1 assuming 5% systematics, but discovery is challenging...

Top Resonance Searches

- Top resonances less competitive this year above ~1.7 TeV, but perhaps possible using jet substructure techniques



$$M_{G'} = 1(2)\ \text{TeV},\ g_A^u = 1.5,\ g_A^t = -2 \text{ and } g_V = 0$$

Next Step at the Tevatron: BB Asymmetry

- D0 data for Tops interesting, but...

- Is a measurement of the B Quark or C Quark FB Asymmetry possible?
- Another check, provides very useful information on energy dependence to discriminate NP from SM

A BB Asymmetry?

Let's consider events above 450 GeV, have 3000-10,000 events to work with after applying kinematic acceptances.

Difficult Questions - how can we optimally tag and measure the sign of the Bs (or Cs)?

Also considered by Strassler, 1102.0746

BB Guesswork

- Need 1 or 2 leptons for signing (0.2 probability of semi-leptonic decay),
- Need 1 or 2 b-tags (~0.3 b-tag rate)
- Must contend with B mixing (~13%)
- and leptons from charm decays (looks possible if we lose 50% of events)

BB Guesswork

With 1 b-tag, 1 lepton, and $M_{b\bar{b}} > 450\, GeV$ and assuming equal asymmetry to Tops, find 200 forward and 100 backward events.

Demanding 2 leptons would be a useful check.

Have far more events at lower energies, so an asymmetry there should be visible.

LHC Prospects

- If an Axigluon can (fully) explain the asymmetry, it should be visible in LHC dijet searches this year
- Important to improve contact operator searches, since the Axigluon would be heavy and strongly coupled

Conclusions

- Axigluon arguably most sensible new physics explanation of asymmetry, currently being tested at the LHC
- Other NP explanations also tested
- To understand asymmetry, important to look at Bottom Quarks, perhaps Charm
- Experimental Fluke, Large NNLO, Other SM Effect, or New Physics???