

The top quark forward-backward asymmetry and new physics contributions*

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* Based on work and discussions with S. Jung, A. Pierce and H. Murayama

Measurable Properties of the Top Quark

- Total production cross section
- Decay branching fractions and width
- $t\bar{t}$ invariant mass distribution
- Forward-backward asymmetry
- ... many other properties

With new physics, all are or can be interrelated.

We will start with forward-backward asymmetry.

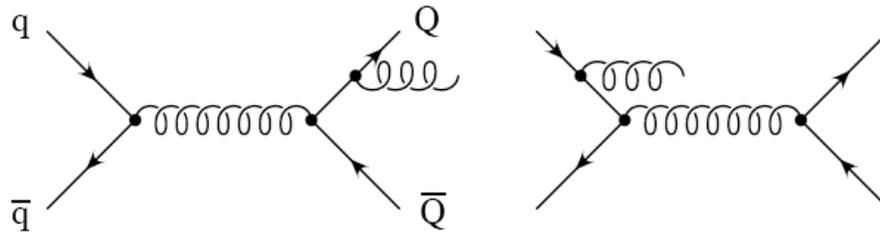
Inspired in part by recent preprint (our main experimental source for this talk):
CDF, “Measurement of the Forward-Backward Asymmetry in $t\bar{t}$ production in 3.2 fb^{-1} of $p\bar{p}$ collisions at 1.96 TeV,” CDF Note 9724 (March 17, 2009). 2

Standard Model Prediction

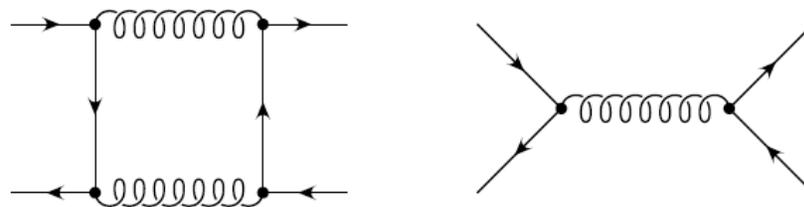
Asymmetry arises at α_s^3 order.

(Close analogy with QED α^3 asymmetry, Berends et al. 1973)

Interference of ISR with FSR:



Interference of box with tree:

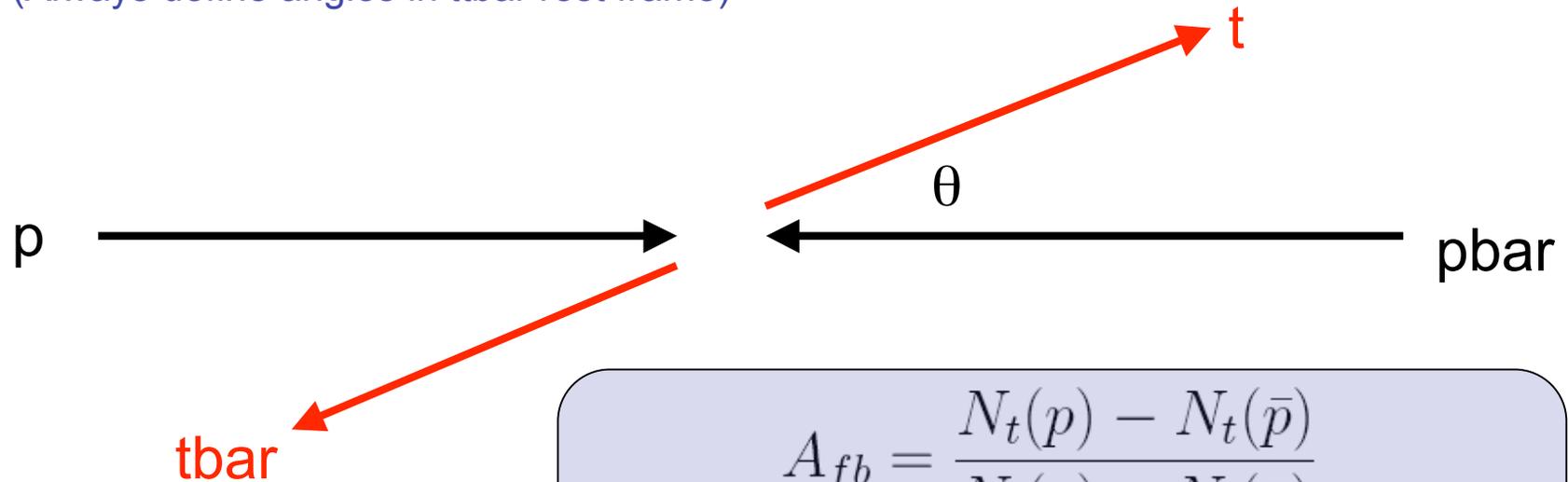


$$A_{FB}^{th} \simeq 0.050 \pm 0.015$$

(Antuñano), Kühn, Rodrigo, PRD '99 (0709.1652)

Top Asymmetry at the Tevatron

(Always define angles in $t\bar{t}$ rest frame)



$$A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$

$N_i(j) = \#$ of particle i in direction of particle j

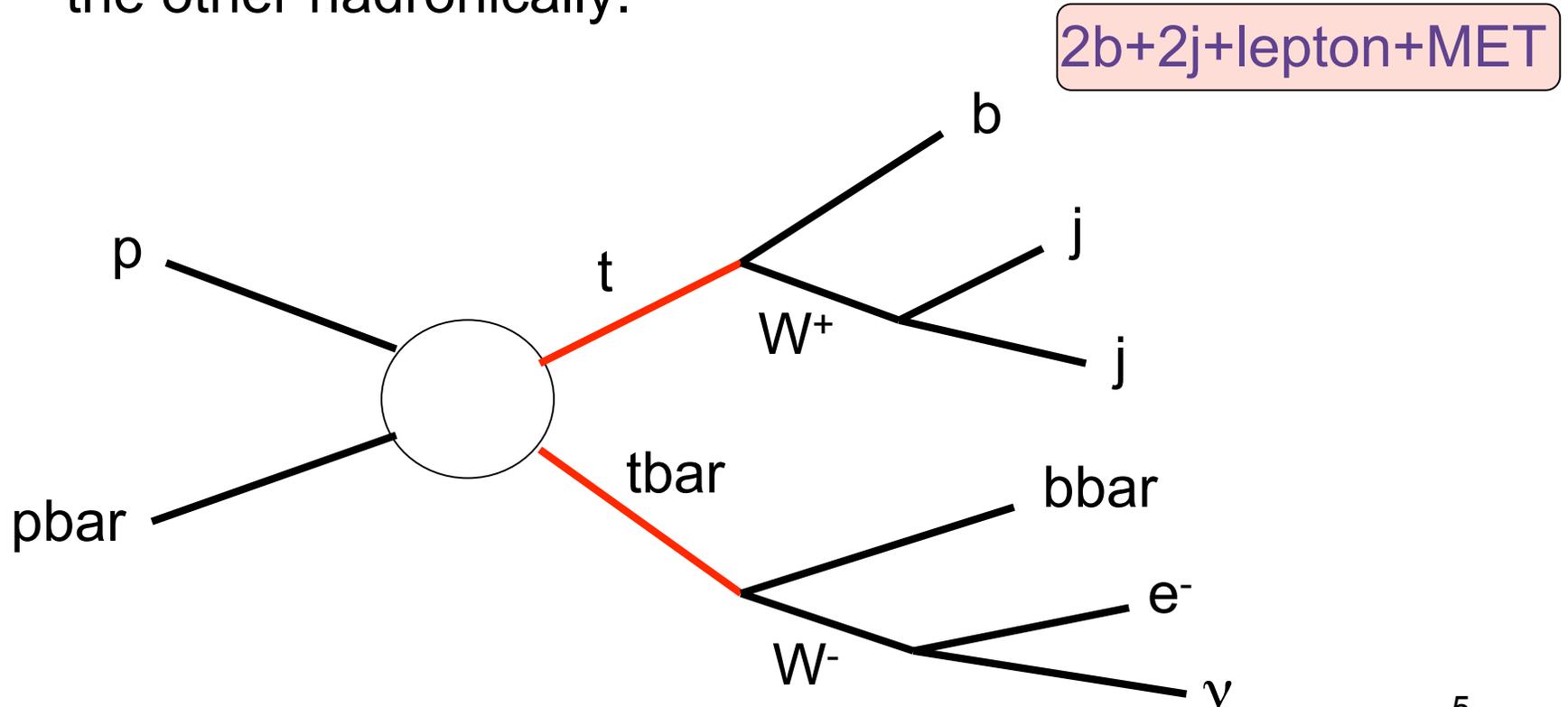
Assuming CP

$$N_{\bar{t}}(p) = N_t(\bar{p})$$

which implies $A_c = A_{fb}$ where $A_c = \frac{N_t(p) - N_{\bar{t}}(p)}{N_t(p) + N_{\bar{t}}(p)}$

What they measure

Actual measurement is made on collection of $t\bar{t}$ events that have one top decaying leptonically and the other hadronically.



Event Selection

- Single lepton with $p_T > 20$ GeV and $|\eta| < 1.1$
- Missing E_T from neutrino: MET > 20 GeV
- 4 or more 'tight jets' $E_T > 20$ GeV, $|\eta| < 2.0$
- At least one jet has 'two tracks that form a secondary vertex (a 'tagged jet')' This is the b jet selection

Surviving events in 3.2 fb^{-1}

From CDF Note 9724

Process	≈ 4 Jets	≥ 5 Jets
W + HF Jets	70.08 ± 21.99	16.48 ± 5.41
Mistags (W+LF)	22.52 ± 5.72	4.91 ± 1.98
Non-W (QCD)	25.04 ± 20.53	8.40 ± 7.53
Single Top	6.62 ± 0.42	1.20 ± 0.08
WW/WZ/ZZ	6.00 ± 0.57	1.57 ± 0.17
Z+Jets	3.89 ± 0.48	0.89 ± 0.11
Top	425.02 ± 58.86	144.06 ± 19.95
Total Prediction	559.15 ± 66.99	177.49 ± 22.23

Remaining top sample

Tops/Background ~ 3.4 ratio

(Total number of $t\bar{t}$ produced in 3.2 fb^{-1} is about 20k, meaning only about 3% of $t\bar{t}$ events survived the selection.)

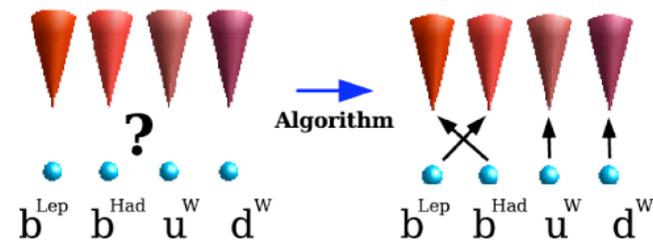
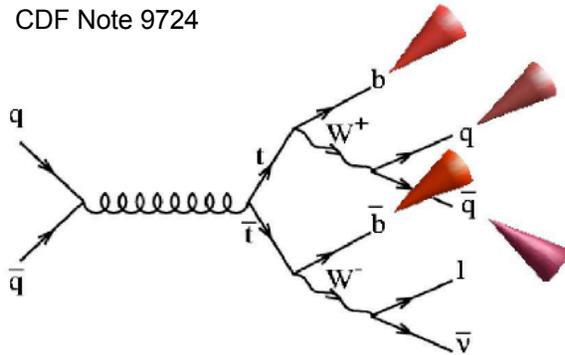
Constructing the asymmetry

Some constraints and assumptions are applied to sample:

- Assume that highest 4 energy jets come from the 4 quarks in $t\bar{t}$ process [tagged b quark(s) are b quark(s)], with significant matching ambiguity
- Reconstruct $p_z(\text{neutrino})$ by $(p_l + p_\nu)^2 = m_W^2$, with 2-fold ambiguity
- Two jets must reconstruct m_W ($W \rightarrow jj$)
- $M_{lvj} = M_t$ and $M_{j(jj)} = M_t$

Matching Algorithm

CDF Note 9724



$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2} \\ + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{blv} - M_{fit})^2}{\Gamma_t^2}$$

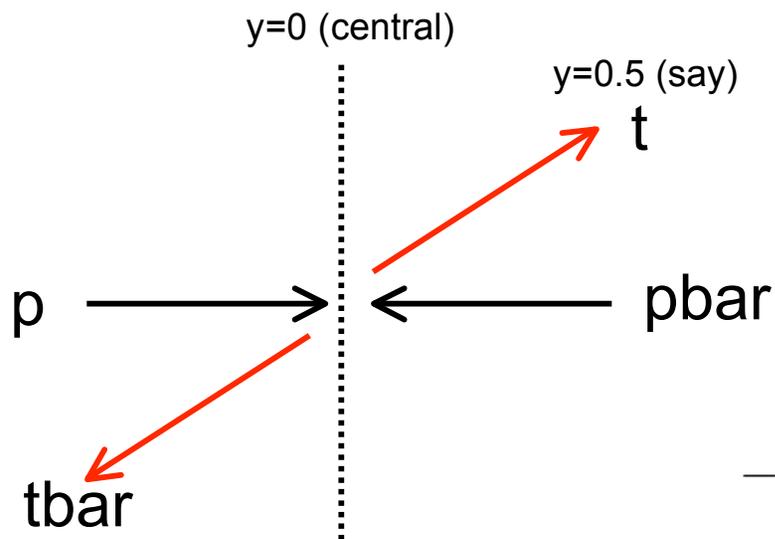
Use MINUIT to minimize χ^2 of each event. Monte Carlo studies say the constrained fit algorithm yields correct match for 60% of the events.

What they measure...

$$A_{fb} = \frac{N(-Q_l \cdot y_{had} > 0) - N(-Q_l \cdot y_{had} < 0)}{N(-Q_l \cdot y_{had} > 0) + N(-Q_l \cdot y_{had} < 0)}$$

y_{had} = rapidity of the hadronically decaying t or \bar{t}

Q_l = lepton charge from the leptonically decaying t or \bar{t}



$$N_t(p) = N(-Q_l \cdot y_{had} > 0)$$

$$N_t(\bar{p}) = N(-Q_l \cdot y_{had} < 0)$$

$$-Q_l \cdot y_{had} = -(-1) \cdot (0.5) = 0.5 \text{ (positive)}$$

Raw Asymmetry

Applying all this to the data they get

$$A_{FB}^{raw} = 0.098 \pm 0.036$$

But this is “raw asymmetry” from data, which has several problems that must be unfolded to get the correct/true asymmetry.

1. Background pollution (W+jets, etc.). This can be understood, measured and subtracted by much larger set of “antitagged” events (events without b quarks).
2. Kinematic fitter smears true top quark rapidities (only dilutes asymmetry, but does not generate it)
3. Event selection cuts out some ttbar events -- concern is that acceptance may be biased w.r.t. top rapidity (small effect).

Forward-Backward Asymmetry Measurement

$$A_{FB} = 0.193 \pm 0.065^{stat} \pm 0.024^{syst}$$

Why is this so interesting?

- 3σ away from zero -- nonzero, measured property of the top quark.
- About 2σ above Standard Model prediction.
- The actual measurement -- the asymmetry seen by events -- is persistently large at CDF and D0.

$$A_{FB}^{th} \simeq 0.05$$

Previous Measurements

$$A_{FB} = 0.20 \pm 0.11^{stat} \pm 0.047^{syst} \quad (0.695 \text{ fb}^{-1} \text{ CDF T. Schwarz Thesis})$$

$$A_{FB} = 0.19 \pm 0.09^{stat} \pm 0.02^{syst} \quad (0.9 \text{ fb}^{-1} \text{ D0 0712.0851})$$

$$A_{FB} = 0.17 \pm 0.07^{stat} \pm 0.04^{syst} \quad (1.9 \text{ fb}^{-1} \text{ CDF 0806.2472})$$

$$A_{FB} = 0.193 \pm 0.065^{stat} \pm 0.024^{syst} \quad (3.2 \text{ fb}^{-1} \text{ CDF 9724, 17 Mar 2009})$$

New Physics?

Interesting to ask what new physics could cause this.

Is it possible to have large asymmetry but not affect other observables too much (e.g., top cross section)?

WARNING!!

The models and theories you are about to see may be disturbing to young viewers.

Going forward: if you ever think nature could not be *that ugly*, just remember it produced these (next slide):



Axigluons

So-called chiral color theories of various origins.
Frampton, Glashow, '87, and others....

$SU(3)_L \times SU(3)_R$ breaks to $SU(3)_C$
Leaving 8 massive axigluons.
Coupling is QCD strength but with γ^5

Maximal charge asymmetry as tree-level $\bar{t}\gamma^\mu\gamma^5t$
is relative C odd to $\bar{t}\gamma^\mu t$.

Axigluon limitology

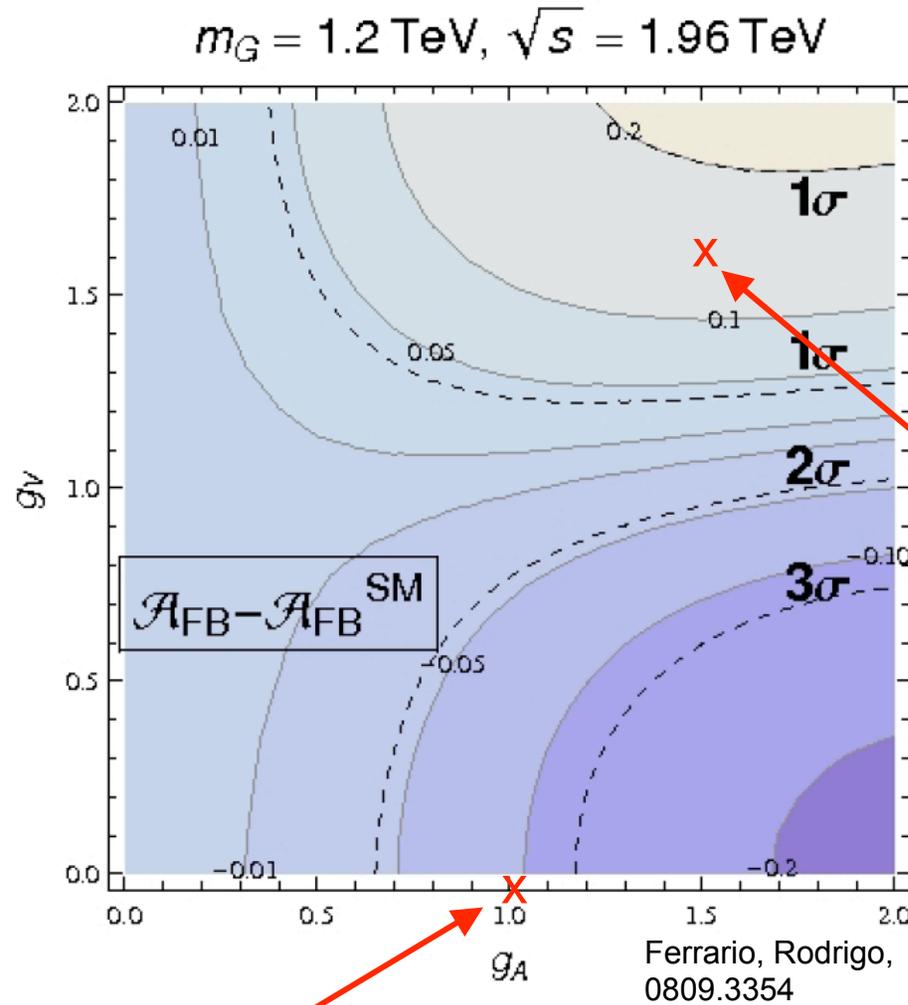
Problem is the asymmetry goes wrong way!

$$A_{\text{FB}} = -0.13 \text{ for } m_A = 1 \text{ TeV}$$

From asymmetry measurement,
 $m_A > 1.2 \text{ TeV}$ at 90% CL (2 yrs old limit now and based on 695 pb^{-1} of data)

Direct limits from LEP1 (Z to q qbar A) and
Tevatron Resonance hunting:
 $m_A > 1.13 \text{ TeV}$ at 95% CL

More general g_V - g_A couplings

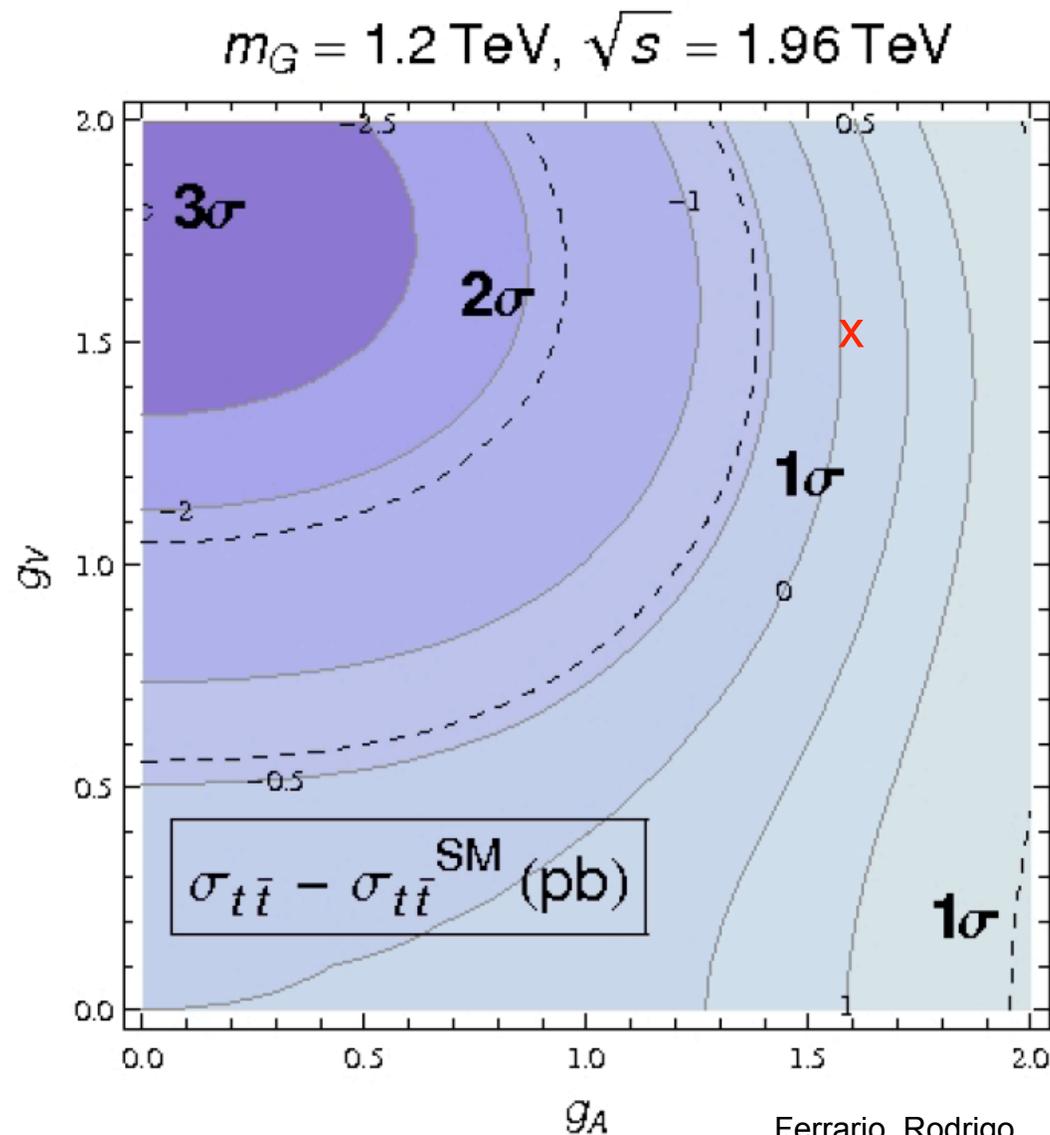


Couplings are with respect to the QCD gauge coupling.

This point looks good!

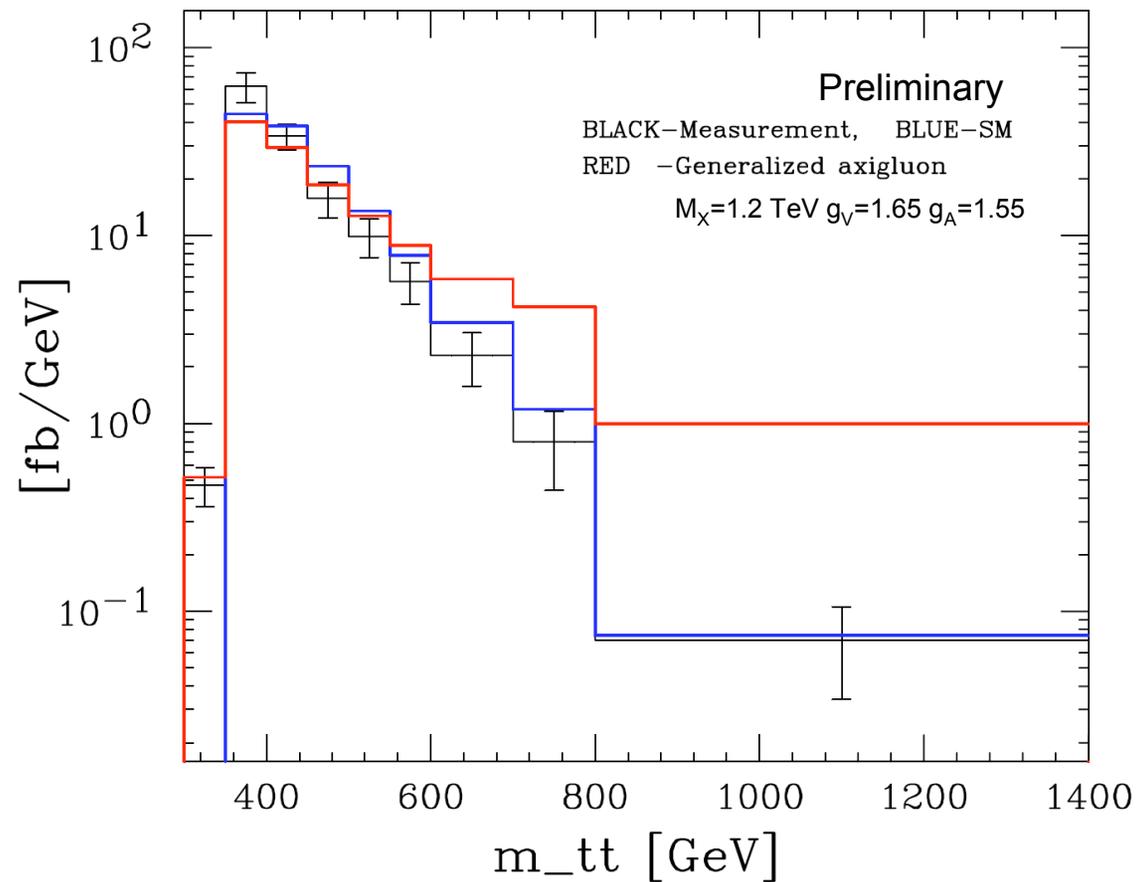
Pure axigluon coupling (large negative contribution to \mathcal{A}_{FB})

Top cross-section constraint



Consistency with total rate is ok.

Difficulty with differential cross-section

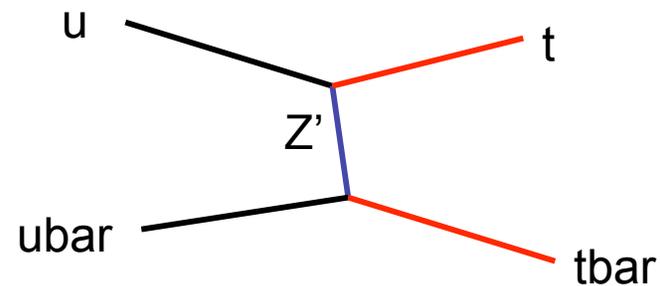


Data from CDF, "Measurement of the $t\bar{t}$ differential cross section ... in 2.7 fb^{-1} of CDF II Data", CDF note 9602 (11 Nov 08).

t-channel approach

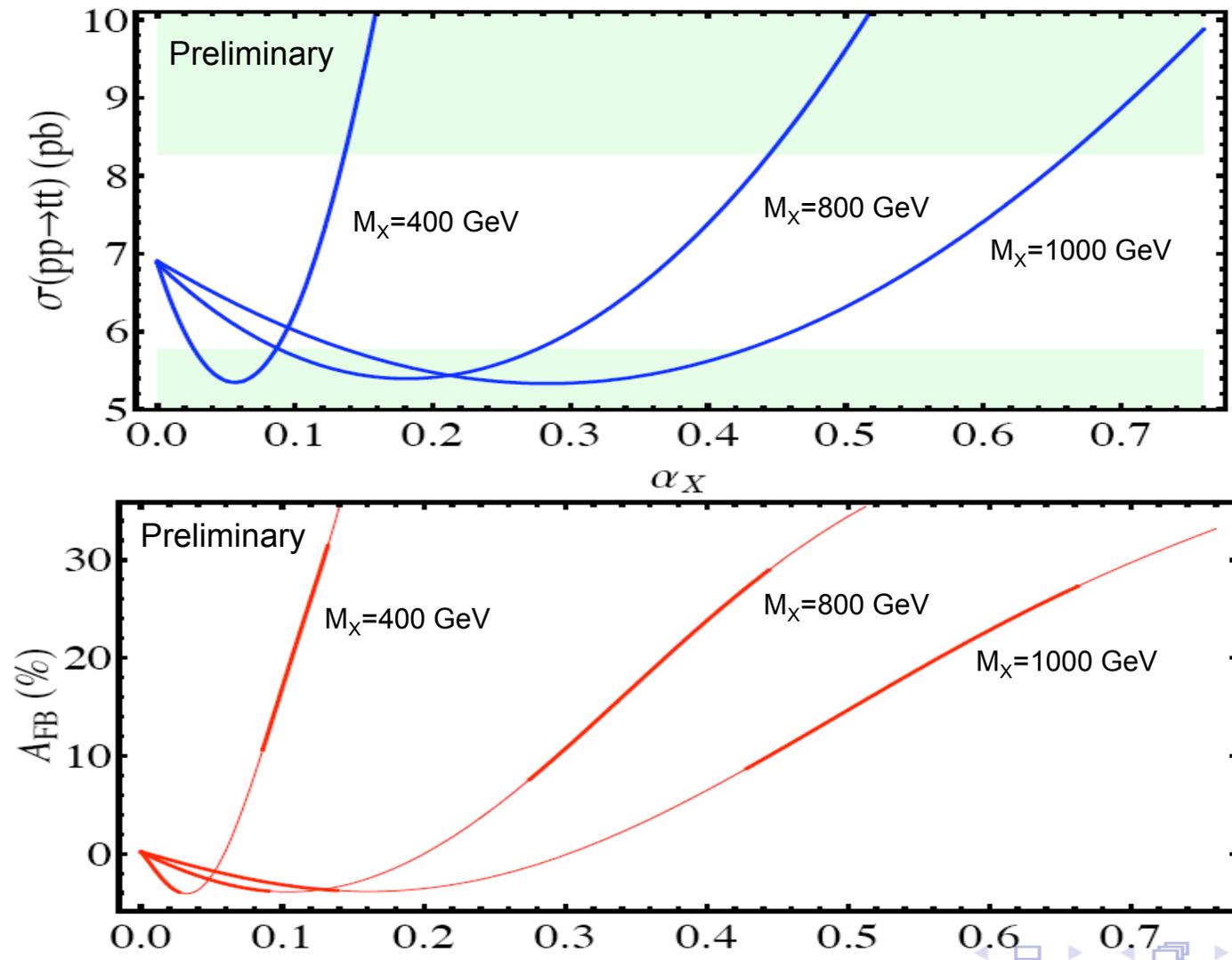
Start with a simple model that can produce top quarks via t-channel exchange, with hopes of less disruption to $t\bar{t}$ invariant mass distribution:

$$Z'_\mu \bar{u} \gamma^\mu P_R t + h.c.$$

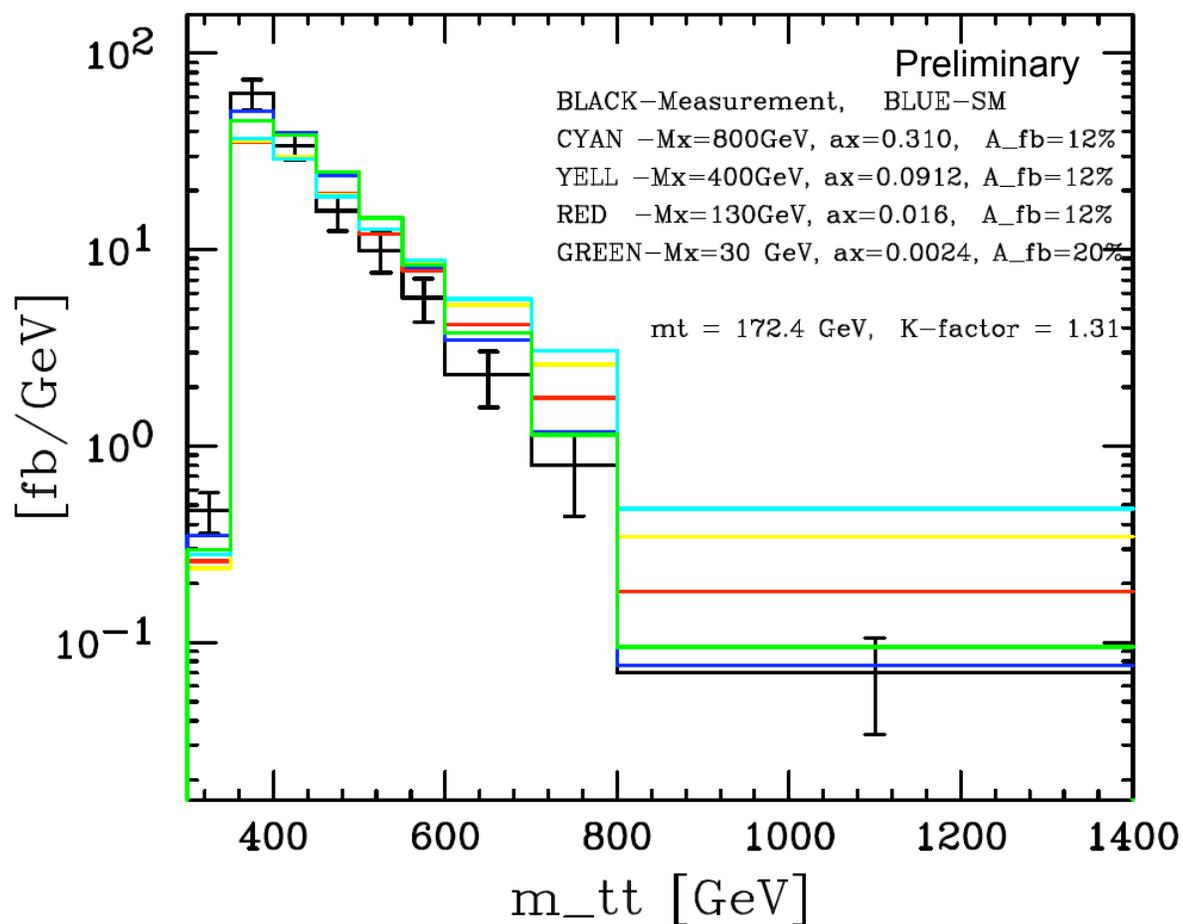


Theory challenges, that can be met, include flavor physics constraints, and an anomaly free model.

Cross-section and Asymmetry



Differential cross-section

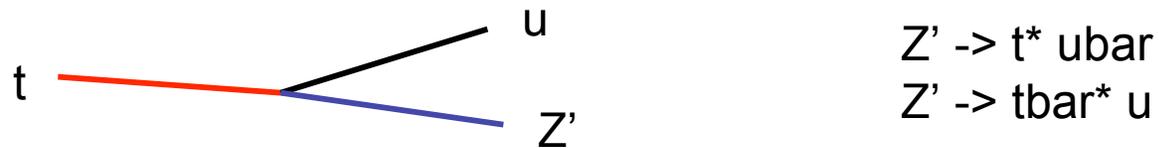


Problem with
invariant mass
distribution unless
 $M_x < 200\text{ GeV}$

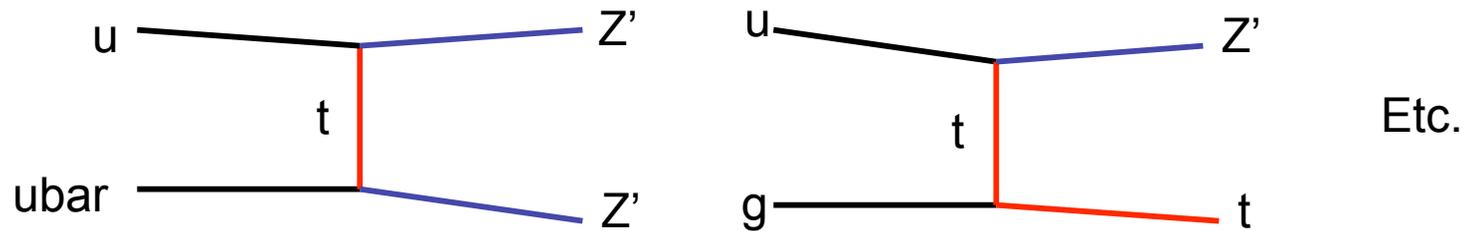
Data from CDF, "Measurement of the $t\bar{t}$ differential cross section ... in 2.7 fb^{-1} of CDF II Data", CDF note 9602 (11 Nov 08).

Problem with small Z' mass

Top quark can decay to Z' : $t \rightarrow Z' u$ --- limits about 10%

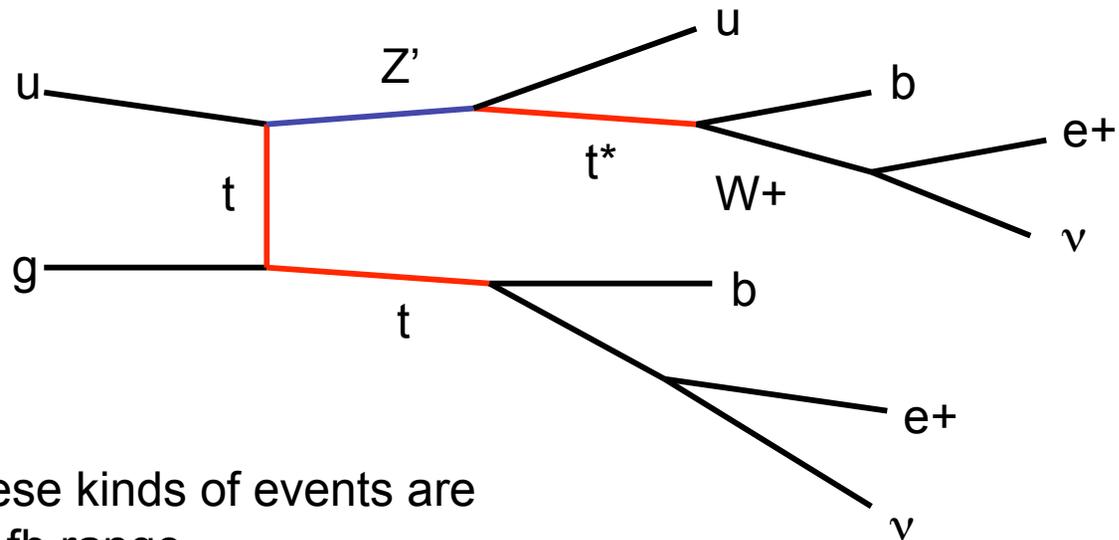


Z' can be produced efficiently and pollute top sample and create 'pink elephant' phenomenology



Z' production constraints

Among other things, can produce events of the type: SS Dilepton + b + MET



Limits on these kinds of events are in the 5 - 10 fb range.

Results for Light Z'

$M_x=100\text{GeV}$ ($Br(t \rightarrow uZ') = 29.8\%$) $A_{\text{FB}} = 0.17$ ($\alpha_x = 0.013$)

Preliminary	σ (pb)	measured σ^*	$tt + \bar{t}\bar{t}$	measured [†]
$p\bar{p} \rightarrow t\bar{t}$ (SM)	6.85	$7.1 \pm 0.8(1+j)$, $6.7 \pm 0.98(1+l)$	0	0
$p\bar{p} \rightarrow t\bar{t}$	5.85	4.45, 3.18	1.49	1.08
$tZ', \bar{t}Z'$	4.03	1.03, 0.57	2.02	0.57
$t\bar{u}Z', \bar{t}uZ'$	6.98	3.76, 1.99	3.49	1.99
$Z'Z'$	0.73	0.06, 0.019	0.37	0.019
total		9.31, 5.76	7.37pb	2.66pb

$\sigma(\text{SS dilep}) \sim 50 \text{ fb}$
after br fractions.

Several
times too
large

$\sigma(\text{SS dilep}) \sim 35 \text{ fb}$
after br fractions.

$M_x=160\text{GeV}$ ($Br(t \rightarrow uZ') = 2.8\%$) $A_{\text{FB}} = 0.15$ ($\alpha_x = 0.024$)

Preliminary	σ (pb)	measured σ	$tt + \bar{t}\bar{t}$	measured
$p\bar{p} \rightarrow t\bar{t}$ (SM)	6.85	$7.1 \pm 0.8(1+j)$, $6.7 \pm 0.98(1+l)$	0	0
$p\bar{p} \rightarrow t\bar{t}$	5.85	5.64, 5.18	0.15	0.15
$tZ', \bar{t}Z'$	2.28	2.22, 1.01	1.14	1.01
$t\bar{u}Z', \bar{t}uZ'$	0.71	0.77, 0.31	0.36	0.31
$Z'Z'$	0.64	0.55, 0.25	0.32	0.25
total		9.18, 6.755	1.97	1.725

* Lowering α_x gets ttbar cross-section better/fine, but SS dilepton problem remains.

Rock and a Hard Place

Rock: Large M_X value means $t\bar{t}$ differential distribution in conflict with data.

Hard Place: Small M_X value means too many exotic events from Z' production.

We're trying to find intermediate value that works

Conclusion

CDF and D0 finding tantalizing large top quark asymmetry.

Very hard to get over 15%, say, by way of new physics without creating stresses and conflicts with other data.