Overview of models for the $t\bar{t}$ asymmetry

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Sant Feliu de Guíxols, September 29th 2011

Timeline of Tevatron measurements

1995 – 2010

up to $\sim 2\sigma$ asymmetry excess in D0 & CDF measurements

01/2011

high-mass measurement by CDF triggers paper flood

$A_{FB} = 0.158 \pm 0.075$ (inclusive)	SM: 0.058	1.3σ
$A_{FB} = 0.475 \pm 0.114$ ($m_{t\bar{t}} > 450$ GeV)	SM: 0.088	3.4σ

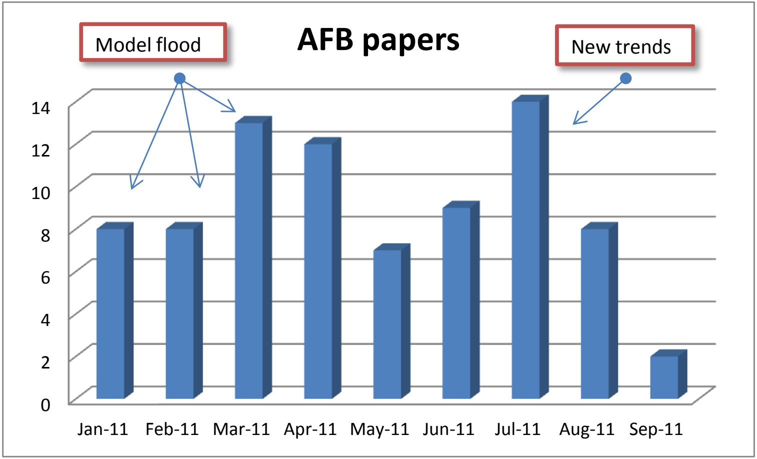
07/2011

long awaited D0 measurement confirms inclusive but not high-mass A_{FB}

updated SM predictions reduce discrepancies Hollik, Pagani '11

$A_{FB} = 0.196 \pm 0.065$ (inclusive)	SM: 0.0893	1.6σ
$A_{FB} \sim 0.2$ ($m_{t\bar{t}} > 450$ GeV)	SM: 0.139	

Timeline of models



☞ Granada: 2 groups with 9.9% of these

Models: lessons from experiment

Important constraint from $\sigma_{\text{exp}} \sim \sigma_{\text{SM}}$

$$\sigma_{\text{exp}} = 7.50 \pm 0.48 \text{ pb} \qquad \text{CDF}$$

$$\sigma_{\text{SM}} = \begin{cases} 7.46^{+0.66}_{-0.80} \text{ pb} & \text{Langenfeld et al '09} \\ 6.30 \pm 0.19^{+0.31}_{-0.23} \text{ pb} & \text{Ahrens et al '10} \end{cases}$$

$\sigma(t\bar{t}) = \sigma_{\text{SM}} + \delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim \sigma_{\text{SM}}$ but A_{FB} large

☞ $$\begin{cases} \delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim 0 & \to \text{'tuned' cancellation} \\ \delta\sigma_{\text{int}} \sim 0 \text{ but not } A_{\text{FB}} & \to \delta\sigma^{\text{F}}_{\text{int}} = -\delta\sigma^{\text{B}}_{\text{int}} \end{cases}$$

These two possibilities are radically different:

- $\delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim 0$ occurs at a given CM energy for a given coupling
- $\delta\sigma^{\text{F}}_{\text{int}} = -\delta\sigma^{\text{B}}_{\text{int}}$ arises from vertex structure (e.g. axial), at all energies

Models: lessons from theory

A_{FB} is an effect competing with QCD

★ most likely, new physics in $q\bar{q} \to t\bar{t}$

★ and expected at the tree level

Now, which can be the "new physics" for $q\bar{q} \to t\bar{t}$?

The possibilities are limited by group theory. Only 18!

☞ Lagrangian terms are $\mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ singlets: types of bosons determined by quantum numbers of quarks

Colour:

$$3 \otimes \bar{3} = 8 \oplus 1$$

$$3 \otimes 3 = 6 \oplus \bar{3}$$

Isospin:

$$2 \otimes 2 = 3 \oplus 1$$

$$2 \otimes 1 = 2$$

$$1 \otimes 1 = 1$$

Hypercharge:

$$\sum Y = 0$$

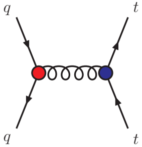
Vectors		Scalars	
Label	Rep.	Label	Rep.
$\mathcal{B}_\mu$	$(1,1)_0$	ϕ	$(1,2)_{-\frac{1}{2}}$
$\mathcal{W}_\mu$	$(1,3)_0$	Φ	$(8,2)_{-\frac{1}{2}}$
$\mathcal{B}^1_\mu$	$(1,1)_1$	ω^1	$(3,1)_{-\frac{1}{3}}$
$\mathcal{G}_\mu$	$(8,1)_0$	Ω^1	$(\bar{6},1)_{-\frac{1}{3}}$
$\mathcal{H}_\mu$	$(8,3)_0$	ω^4	$(3,1)_{-\frac{4}{3}}$
$\mathcal{G}^1_\mu$	$(8,1)_1$	Ω^4	$(\bar{6},1)_{-\frac{4}{3}}$
$\mathcal{Q}^1_\mu$	$(3,2)_{\frac{1}{6}}$	σ	$(3,3)_{-\frac{1}{3}}$
$\mathcal{Q}^5_\mu$	$(3,2)_{-\frac{5}{6}}$	Σ	$(\bar{6},3)_{-\frac{1}{3}}$
$\mathcal{Y}^1_\mu$	$(\bar{6},2)_{\frac{1}{6}}$		
$\mathcal{Y}^5_\mu$	$(\bar{6},2)_{-\frac{5}{6}}$		

Building models

- ★ A model can have a number of particles and multiplets in any of these representations.
- ★ You can parameterise light or heavy new physics with these 18 representations, in the same way as you use effective operators
- ★ In most of the proposed models the contributions to A_{FB} arise from a single new particle in one of these representations
- ★ This new particle can contribute to $q\bar{q} \to t\bar{t}$ in s, t or u channel.

  ☞ quite a difference !!!

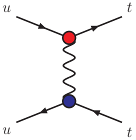
Most popular models



s channel:

$\mathcal{G}_\mu \sim (8,1)_0$

0809.3354 , 0906.0604 , 0911.2955 , 1007.0243 , 1011.6380 , 1011.6557 , 1101.2902 , 1101.5203 , 1103.0956 1104.1917 , 1105.3158 , 1105.3333 , 1106.0529 , 1106.4054 , 1107.0978 , 1107.1473 , 1107.2120 , 1107.5769 , 1109.0648



t channel:

$Z' \sim (1,1)_0$

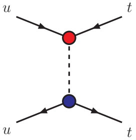
0907.4112 , 1101.4456 , 1101.5625 , 1102.0545 , 1103.1266 1103.4835 , 1104.1385 , 1104.3139 , 1106.5982 , 1108.0350 , 1108.1802

$W' \sim (1,1)_1$

0908.2589 , 1002.1048 , 1003.3461 , 1101.1445 , 1101.5392 , 1102.0279 1104.0083 , 1105.4606

$\phi \sim (1,2)_{-\frac{1}{2}}$

1104.4782 , 1107.0841 , 1107.4350 , 1108.4005



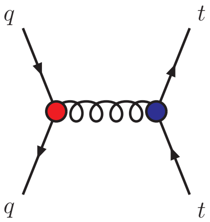
u channel:

$\omega^4 \sim (3,1)_{-\frac{4}{3}}$

$\Omega^4 \sim (\bar{6},1)_{-\frac{4}{3}}$

0911.3237 , 0911.4875 , 0912.0972 , 1007.2604 , 1102.3374 , 1102.4736 , 1103.2757 , 1108.4027

s-channel: coloured resonance $\mathcal{G}_\mu$



Requires $\bar{u}\gamma^\mu u\,\mathcal{G}_\mu$ / $\bar{d}\gamma^\mu d\,\mathcal{G}_\mu$ couplings as well as $\bar{t}\gamma^\mu t\,\mathcal{G}_\mu$

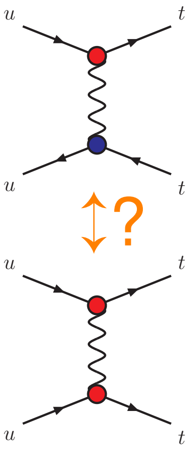
couplings to *uu* and *dd* small, otherwise $\mathcal{G}_\mu$ gives dijet production (unobserved)

larger coupling to *tt* natural in extra dimensions

Colour octet: features

- Interference $\delta\sigma_{\text{int}}$ identically zero (at all energies) if either coupling to $q\bar{q}$ or $t\bar{t}$ axial
- Asymmetry maximised respect to $\delta\sigma$ if both couplings axial (old friend axigluon)
- Distinctive signature: peak (bump) in the $m_{t\bar{t}}$ distribution
- Non-observation of peak $\rightarrow$ $\mathcal{G}_\mu$ assumed heavy
- BUT current LHC limits begin to be problematic:
  too large couplings may be required to generate A_{FB}
- Alternative: *light* gluons (more on this later)

t-channel: Z' ($\mathcal{B}_\mu$)



Requires flavour-changing *ut* couplings

$\bar{u}\gamma^\mu t\, Z'_\mu = \left(\bar{t}\gamma^\mu u\, Z'_\mu\right)^\dagger$ provided Z' is real

In this case, a distinctive signature is *tt* production, unobserved (more on this later)

For a *complex* Z': forget all this

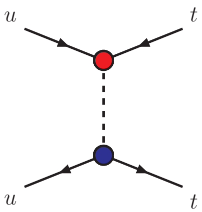
Jung et al '11

Z': features

- *Negative* Z' − SM interference decreases $A_{\rm FB}$
- A positive contribution to $A_{\rm FB}$ and agreement with Tevatron $\sigma(t\bar{t})$ require large Z' coupling and cancellation $\delta\sigma_{\rm int} + \delta\sigma_{\rm quad} \sim 0$
- Cancellation cannot happen at LHC too ➞ excess at $t\bar{t}$ tail
- Putting all together:

agreement with Tevatron $\sigma(tt)$	✔	➞ $M_{Z'} \leq 360$ GeV
positive contribution to $A_{\rm FB}$	✔	
tail $\leq 3 \times$ SM for $m_{t\bar{t}} > 1$ TeV	✔	

u-channel: exotic scalars Ω^4 / ω^4



Couplings: $\bar{u}\, t^c\, \Omega^4 \,/\, \omega^4$, $\overline{t^c}\, u\, \Omega^4 \,/\, \omega^4$

Ω^4 can have (but unrelated)
① $\bar{u}\, u^c + \overline{u^c}\, u$
② $\bar{t}\, t^c + \overline{t^c}\, t$

① gives $uu \to uu$ (dijet resonance)

①+② give $uu \to tt$ (resonant tt)

explicit models avoid these . . .

Grinstein et al '11

Ligeti et al '11

ω^4 flavour-antisymmetric couplings

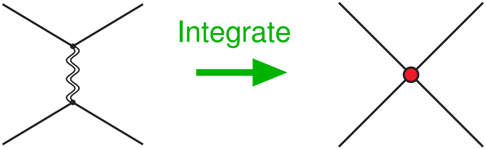
u-channel: features

- The contribution to A_{FB} is negative for small Ω^4 / ω^4 masses
  ☞ u-channel propagator prefers *backward* tops !!!
- Numerator does not, and wins for large M
- $M \gtrsim 220$ GeV required for positive A_{FB} at Tevatron
- Going to high m_{tt} you will finally 'see' u-channel propagator
  ☞ interesting for LHC

no-channel: effective framework

Effective operators parameterise effects of new physics at scale $\Lambda > v$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_6 + \ldots \qquad \mathcal{L}_6 = \sum_x \frac{C_x}{\Lambda^2} O_x$$



(new) heavy VB   4-fermion interaction

couplings g_{ij}
masses M } → operator coefficients C_x , $\Lambda \equiv M$

- ★ 'Model-independent approach': using them you can parameterise corrections from any decoupling heavy physics
- ★ This has been done in several places with several approximations

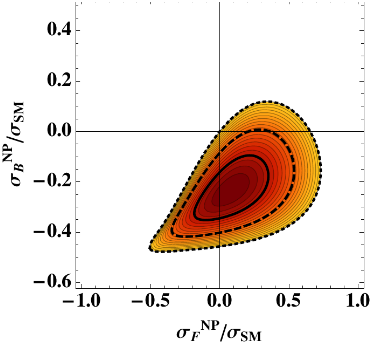
  $1/\Lambda^2$: Jung et al '09 '10, Zhang, Willenbrock '10, Degrande et al '10 '11

  $1/\Lambda^4$: JAAS '10, Delaunay et al '11, JAAS & MPV '11
- ★ Note that experiments tell us that in some cases (e.g. Z', W') the NP must be light ☞ effective operators not applicable
- ★ Still in this case, operators are good for semi-quantitative descriptions (up to factors of $2-3$)

See also talks by Ko and Géraldine

Application

It has been stressed that NP must interfere, either looking at data . . .



Grinstein et al ’11

$$\left.\begin{array}{l}\delta\sigma^F > 0 \\ \delta\sigma^B < 0\end{array}\right\} \rightarrow \text{interference}$$

. . . and from effective operator analysis Delaunay et al ’11

BUT. . . is this really a restriction?

Interfering operators – vector bosons

JAAS & MPV ’11

	C^{3113}_{qq}	$C^{1133}_{qq'}$	C^{3113}_{uu}	$C^{3311}_{ud'}$	C^{1331}_{qu}	C^{3113}_{qu}	C^{3113}_{qd}
$\mathcal{B}_\mu$	$-\lvert g^q_{13}\rvert^2$	–	$-\lvert g^u_{13}\rvert^2$	–	–	–	–
$\mathcal{W}_\mu$	$\lvert g_{13}\rvert^2$	$-2\lvert g_{13}\rvert^2$	–	–	–	–	–
$\mathcal{G}_\mu$	$\frac{1}{6}\lvert g^q_{13}\rvert^2$	$-\frac{1}{2}g^q_{11}g^q_{33}$	$\frac{1}{6}\lvert g^u_{13}\rvert^2 - \frac{1}{2}g^u_{11}g^u_{33}$	$-\frac{1}{4}g^u_{33}g^d_{11}$	$\frac{1}{2}g^q_{11}g^u_{33}$	$\frac{1}{2}g^q_{33}g^u_{11}$	$\frac{1}{2}g^q_{33}g^d_{11}$
$\mathcal{H}_\mu$	$-\frac{1}{6}\lvert g_{13}\rvert^2 - g_{11}g_{33}$	$\frac{1}{3}\lvert g_{13}\rvert^2 + \frac{1}{2}g_{11}g_{33}$	–	–	–	–	–
$\mathcal{B}^1_\mu$	–	–	–	$-\frac{1}{2}\lvert g_{13}\rvert^2$	–	–	–
$\mathcal{G}^1_\mu$	–	–	–	$\frac{1}{12}\lvert g_{13}\rvert^2$	–	–	–
$\mathcal{Q}^1_\mu$	–	–	–	–	–	–	$\lvert g_{13}\rvert^2$
$\mathcal{Q}^5_\mu$	–	–	–	–	$\lvert g_{31}\rvert^2$	$\lvert g_{13}\rvert^2$	–
$\mathcal{Y}^1_\mu$	–	–	–	–	–	–	$-\frac{1}{2}\lvert g_{13}\rvert^2$
$\mathcal{Y}^5_\mu$	–	–	–	–	$-\frac{1}{2}\lvert g_{31}\rvert^2$	$-\frac{1}{2}\lvert g_{13}\rvert^2$	

Trivially: all rows non-empty → All vector bosons interfere

unless you don’t want them to

Interfering operators – scalars

JAAS & MPV '11

	C_{qq}^{3113}	$C_{qq'}^{1133}$	C_{uu}^{3113}	$C_{ud'}^{3311}$	C_{qu}^{1331}	C_{qu}^{3113}	C_{qd}^{3113}
Φ	–	–	–	–	$-\frac{1}{12}\lvert g_{13}^u\rvert^2$	$-\frac{1}{12}\lvert g_{31}^u\rvert^2$	$-\frac{1}{12}\lvert g_{31}^d\rvert^2$
ω^1	–	–	–	$-\frac{1}{4}\lvert g_{13}\rvert^2$	–	–	–
Ω^1	–	–	–	$\frac{1}{8}\lvert g_{13}\rvert^2$	–	–	–
ω^4	–	–	$-2\lvert g_{13}\rvert^2$	–	–	–	–
Ω^4	–	–	$\lvert g_{13}\rvert^2$	–	–	–	–
σ	$-2\lvert g_{13}\rvert^2$	$-2\lvert g_{13}\rvert^2$	–	–	–	–	–
Σ	$\lvert g_{13}\rvert^2$	$\lvert g_{13}\rvert^2$	–	–	–	–	–

Trivially: all rows non-empty → All scalars interfere

unless you don't want them to

As we have stressed, the issue is not whether NP interferes

but *how* it does → implications for LHC

1. Z', W', ω^4: negative, decreases A_{FB} and σ ☹
   - ★ cancellation $\delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim 0$ occurs at a given CM energy
   - ★ once agreement with Tevatron fixed, effects at LHC
2. Ω^4: positive, increases A_{FB} and σ ☺
   - ★ small asymmetries allowed by $\delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \lesssim (\Delta\sigma)_{\text{exp}\oplus\text{th}}$
3. axi-$\mathcal{G}_\mu$: $\delta\sigma^F_{\text{int}} = -\delta\sigma^B_{\text{int}}$, increases A_{FB} keeping σ at $1/\Lambda^2$ ☺☺☺
   - ★ small deviations in σ except for peak enhancement (quadratic)

Now we have LHC! what to look for?

Various smoking guns related to A_{FB}:

- observation of new particles
- like-sign tops
- ...

whose non-observation (as yet) is unconclusive for models' fate

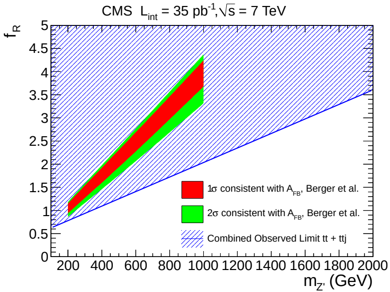
And other probes which are robust and hard-to-evade:

- charge asymmetry A_C measured ✔
- excess in $t\bar{t}$ invariant mass tail waiting ... ✘

☞ should be on top of CMS / ATLAS top physics wishlist !!!

No smoke, no gun: no like-sign tops

CMS plot 1106.2142



Excludes model parameter region consistent with $\sigma = 7.50 \pm 0.48$ pb, high-mass $A_{FB} = 0.475 \pm 0.114$

What if A_{FB} not so large? (D0)

No smoke, no gun: no like-sign tops

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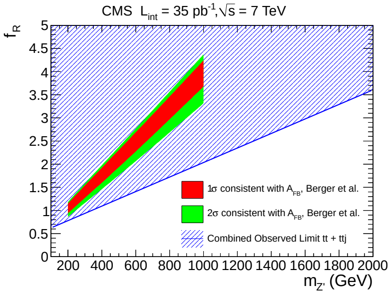
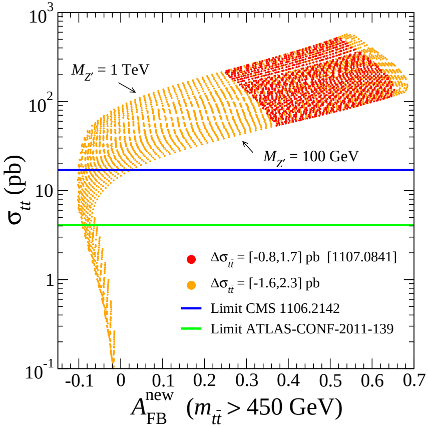


Excludes model parameter region consistent with $\sigma = 7.50 \pm 0.48$ pb, high-mass $A_{FB} = 0.475 \pm 0.114$

What if A_{FB} not so large? (D0)

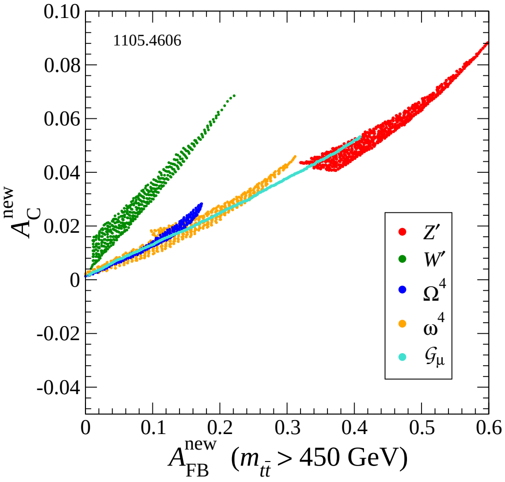
General exclusion plot



Z' coupling from 0 to $\Delta\sigma = 2.3$ pb

$A_{FB}^{new} > 0$ excluded by ATLAS

Predictions for LHC charge asymmetries



How to read the plot

Coloured regions:

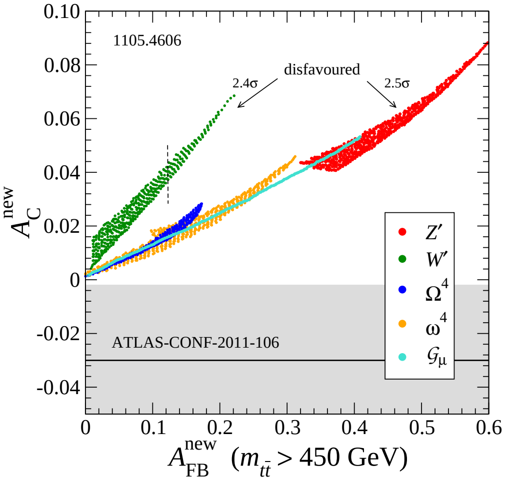
Tevatron $t\bar{t}$ xsec within 1σ

LHC $t\bar{t}$ tail not too large

X: Tevatron high-mass A_{FB}

Y: LHC inclusive A_C
(only NP contributions)

Constraints from LHC charge asymmetries



How to read the plot

Z': disfavoured

W': disfavoured if $A_{FB}^{new} \gtrsim 0.1$
also in D0 measurement

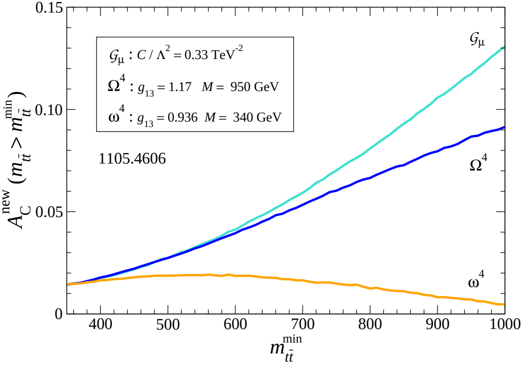
rest: some tension with CDF high-mass A_{FB}

☞ model discrimination already at work !!!

Future prospects with $t\bar{t}$ polarisation: talk by Wang

Next in CMS / ATLAS "to do" list

Measure mass dependence of A_C



How to read the plot

Three benchmark points: same high-mass A_{FB} and inclusive A_C

X: cut on minimum $m_{t\bar{t}}$

Y: A_C

(only NP contributions)

CMS: apparently no A_C enhancement with $m_{t\bar{t}}$ ➙ bad for heavy $\mathcal{G}_\mu$!!!

$t\bar{t}$ invariant mass tail

Measurement not yet addressed by CMS / ATLAS

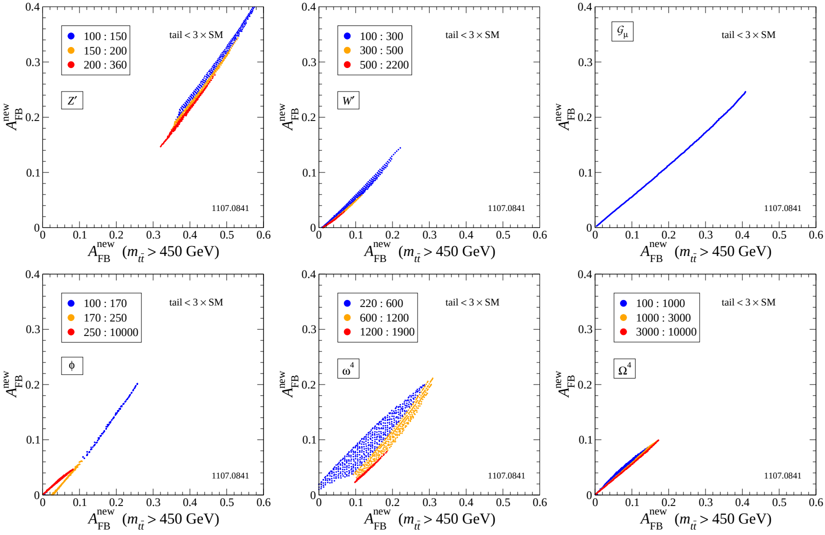
despite its importance was pointed out months ago — Delaunay et al '11, JAAS & MPV '11

But public $m_{t\bar{t}}$ distributions scrutinised by theorists' sharp eye 🙂

Result: $\sim$ agree with the SM — CMS-PAS-EXO-11-055, ATLAS-CONF-2011-123

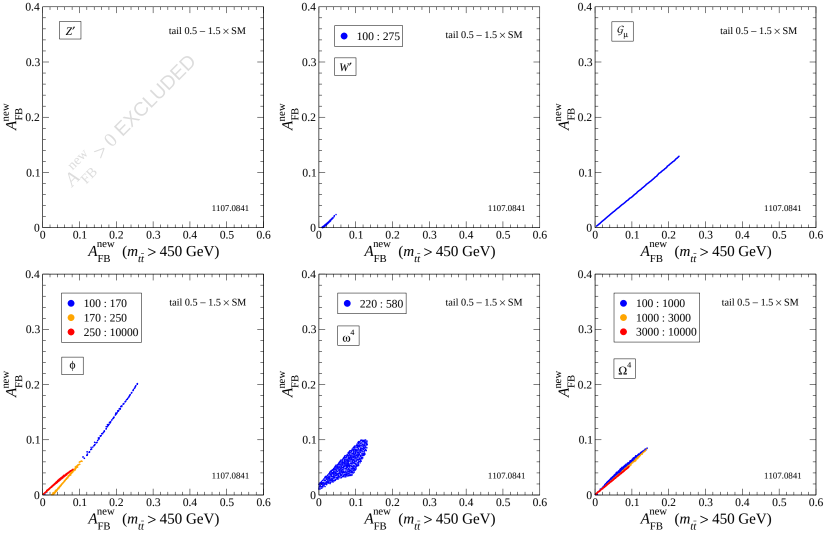
In the absence of a proper limit ➞ make estimations

Constraints from $m_{t\bar{t}}$ tail $\quad \sigma(m_{t\bar{t}} > 1\ \text{TeV}) < 3 \times \text{SM}$



Notice mass dependence: lighter particles less constrained

Constraints from $m_{t\bar{t}}$ tail $\sigma(m_{t\bar{t}} > 1 \text{ TeV}) \in 0.5 - 1.5 \times \text{SM}$



Notice mass dependence: lighter particles less constrained

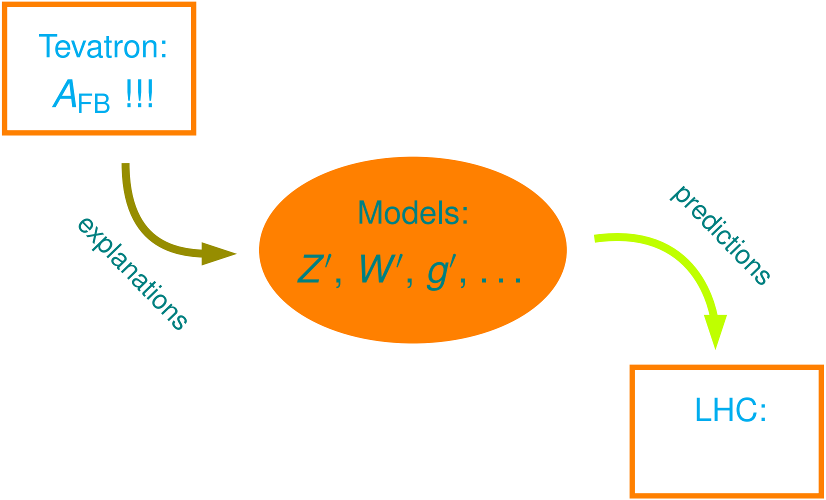
Consequences of $t\bar{t}$ tail ~~measurement~~ theorists' guess

1. Z' models disfavoured
2. W' models disfavoured
3. heavy s-channel $\mathcal{G}_\mu$ must be very heavy and couple strongly
   ☞ ugly non-perturbative model
4. scalar ϕ: no problem ✔
5. exotic scalars: no problem if high-mass A_{FB} moderate

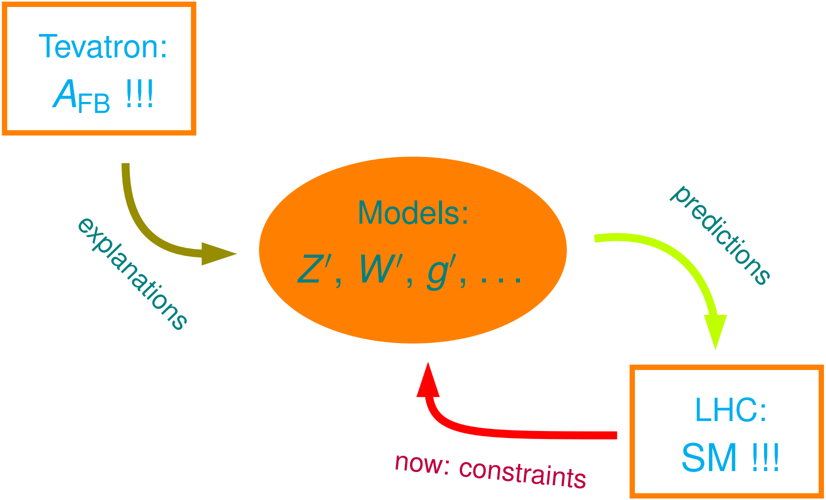
BUT

remember physics is an experimental science: only experimentalists can rule out models with real measurements

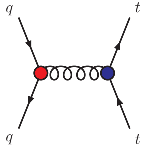
So, what?


Tevatron:
A_{FB} !!!
explanations
Models:
Z', W', g', . . .
predictions
LHC:

So, what?


Tevatron:
A_{FB} !!!
explanations
Models:
Z', W', g', ...
predictions
LHC:
SM !!!
now: constraints

Most popular models . . . after 2011 LHC data

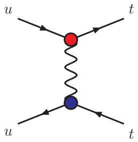


s channel:

$t\bar{t}$ tail $\sim$ SM

$\mathcal{G}_\mu \sim (8,1)_0$

0809.3354 , 0906.0604 , 0911.2955 , 1007.0243 , 1011.6380 , 1011.6557 , 1101.2902 , 1101.5203 , 1103.0956 1104.1917 , 1105.3158 , 1105.3333 , 1106.0529 , 1106.4054 , 1107.0978 , 1107.1473 , 1107.2120 , 1107.5769 , 1109.0648



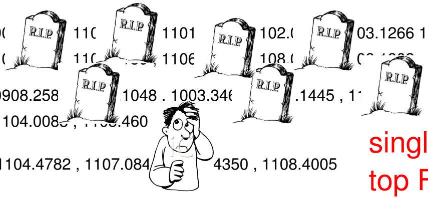
t channel:

$A_C = -0.016$ (CMS), -0.024 (ATLAS)

$Z' \sim (1,1)_0$

$W' \sim (1,1)_1$

$\phi \sim (1,2)_{-\frac{1}{2}}$



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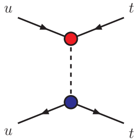
single top?

top FCNC?



u channel:

$t\bar{t}$ tail $\sim$ SM

$\omega^4 \sim (3,1)_{-\frac{4}{3}}$

$\Omega^4 \sim (\bar{6},1)_{-\frac{4}{3}}$

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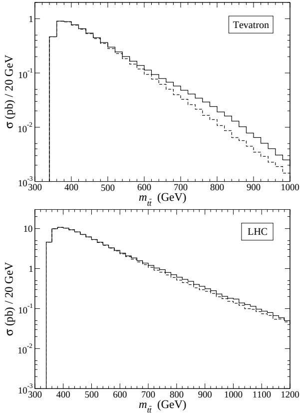
New trends: models without a large $t\bar{t}$ tail

Example: "light" gluons with masses $M \lesssim 1$ TeV

Barceló et al '11, Tavares, Schmaltz '11
Álvarez et al '11, JAAS & MPV '11

- invisible at Tevatron if very wide
- even more at LHC (*gg* fusion)
- small tail: gluon is lighter !!!
- diverse A_{FB} profiles vs $m_{t\bar{t}}$ possible
- small A_C at LHC: not yet disfavoured

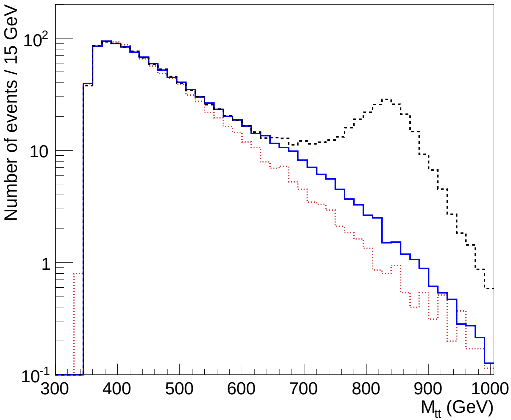


Increasing the gluon width

A large gluon width $\sim 0.5M$ can result, for example, from $\mathcal{G}_\mu \to U\bar{u}$, with U a new heavy quark

Barceló et al '11

$m_{t\bar{t}}$ distribution at Tevatron



How to read the plot

Brown: SM

Black: SM + $\mathcal{G}_\mu$, no U

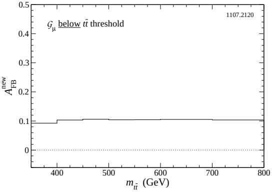
Blue: SM + $\mathcal{G}_\mu$ + U

$A_{FB}(m_{t\bar{t}} > 450 \text{ GeV}) = 0.33$

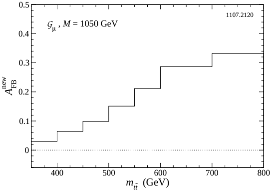
A_{FB} profiles: from D0's flat to CDF's camel

Sustainable model

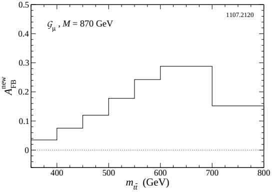
flat



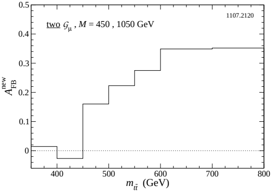
rising



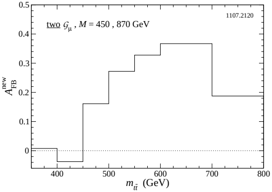
hill



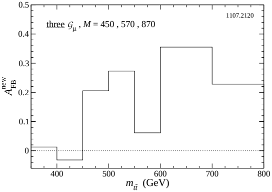
dip-rising



dip-hill



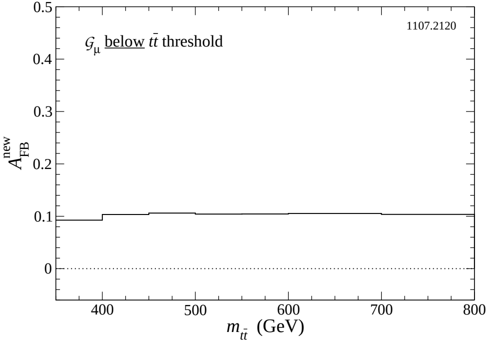
camel



Flat A_{FB} profile: the candidate?

JAAS & MPV '11

Flat profile is in agreement with D0 & CMS and will survive LHC



Gluon $\mathcal{G}_\mu$ with $M \sim 300$ GeV, large coupling to top

$A_{\text{C}}^{\text{new}} = 0.017$ for $A_{\text{FB}}^{\text{new}} = 0.1$

Enhancing A_C: proposals and models

Most models predict $A_\mathrm{C}^{\mathrm{new}} \sim 0.015 - 0.04$, often hard to observe

Various proposals to increase it with kinematical selections

Wang et al '10, Hewett et al '11, Arguin et al '11, Bai, Han '11, JAAS et al '11

Parameters describing $q\bar{q} \to t\bar{t}$, upon which one can cut:

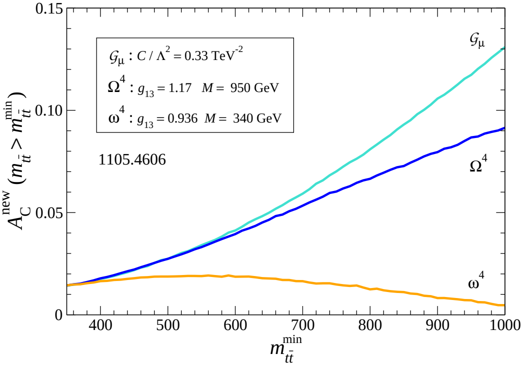
- $\hat{s} = m_{t\bar{t}}$: partonic CM energy
- θ: opening angle in CM frame entering the asymmetry
- $\beta = \dfrac{|p_t^z + p_{\bar{t}}^z|}{E_t + E_{\bar{t}}}$: velocity of CM in LAB frame

  less correlated with $m_{t\bar{t}}$ than $|p_t^z + p_{\bar{t}}^z|$

FAQ #1

Lower cut on $m_{t\bar{t}}$ to increase A_C?

Absolutely not: increase not guaranteed. Remember slides #24, #32



How to read the plot

Three benchmark points: same high-mass A_{FB} and inclusive A_C

X: cut on minimum $m_{t\bar{t}}$

Y: A_C (only NP contributions)

$m_{t\bar{t}}$ dependence is a tool for model discrimination, not to increase A_C

Acting on θ and β can increase A_C

- ★ asymmetry is a forward phenomenon: larger for $\theta \sim 0, \pi$
  [at least in known models]

  ☞ removing central region $\theta \sim \pi/2$ increases A_C

  for light t-channel NP (Z', W') the increase is much higher
  [this should be obvious . . .]

- ★ fraction of $q\bar{q}$ events increases with β

  for moderate cuts on β, asymmetry enhancement
  model-independent

Proposals

1. Forward asymmetry — Hewett et al '11

$$A_{\text{fwd}} = \frac{N(|y_t| > y_C) - N(|y_{\bar{t}}| > y_C)}{N(|y_t| > y_C) + N_{\bar{t}}(|y_{\bar{t}}| > y_C)}$$

☞ selection involving θ, β $\quad \left[y_{\text{CM}} = \frac{1}{2} \log \frac{1 + \beta_{\text{CM}} \cos\theta}{1 - \beta_{\text{CM}} \cos\theta} \right]$

2. Central leptonic, Forward hadronic top — Arguin et al '11

   leptonic top $|\eta| < 2.5$, hadronic top $|\eta| > 2.5$

   ☞ selection involving θ, β

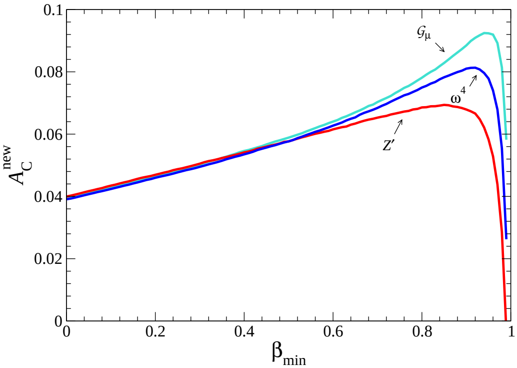
3. Boosted asymmetry — JAAS et al '11

   requirement $\beta > \beta_{\text{min}}$, no selection on θ

Boosted asymmetry

Cutting $\beta > \beta_{\text{min}}$ increases asymmetry

Model-independent increase up to 50% ($\beta_{\text{min}} \simeq 0.6$)



How to read the plot

Asymmetry as a function of the cut β_{min}

$\mathcal{G}_\mu$: *s*-channel

Z': *t*-channel

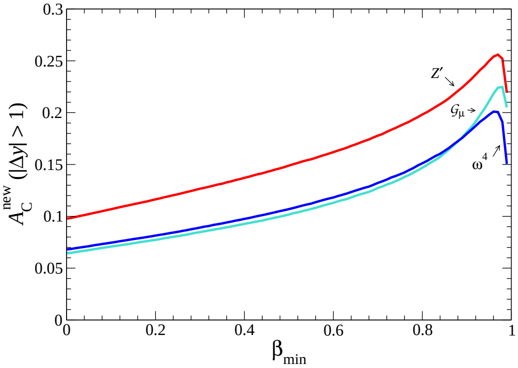
ω^4: *u*-channel

Differences for large β because of bias in $m_{t\bar{t}}$ distribution

Boosted asymmetry

Cut on β complementary to model-dependent enhancements

☞ can still restrict θ and get even larger asymmetries



How to read the plot

Asymmetry for $|\Delta y| > 1$ as a function of the cut β_{min}

$\mathcal{G}_\mu$: *s*-channel

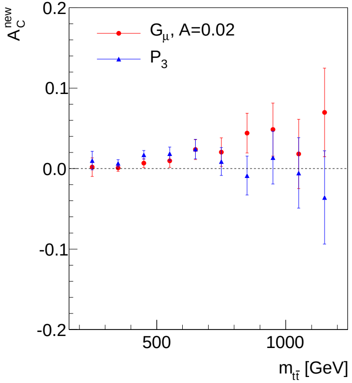
Z': *t*-channel

ω^4: *u*-channel

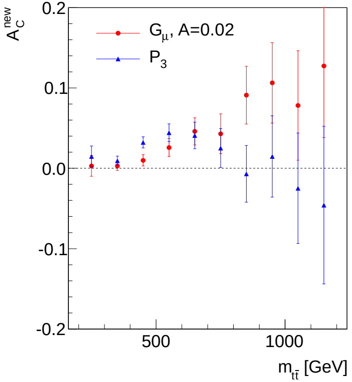
Boosted asymmetry

Cut on β ideal to improve model discrimination

no cut



$\beta > 0.6$

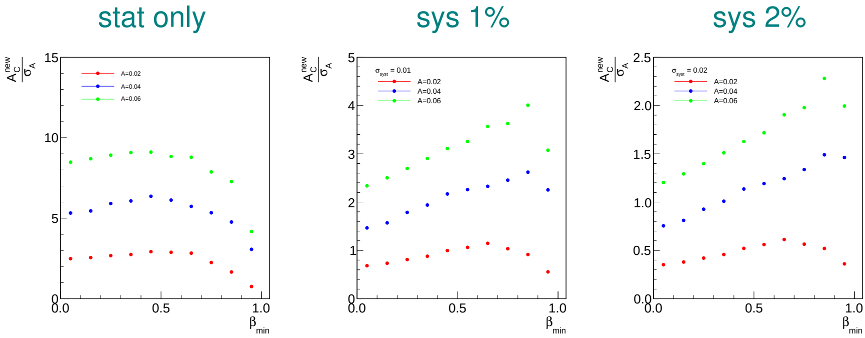


Red: heavy colour octet

Blue: $M = 870$ GeV ($A < 0$ for $m_{t\bar{t}} > M$)

Significance of boosted asymmetry

Luminosity: 10 fb^{-1} efficiency $\sim$ ATLAS



Red: $A_C^{\text{new}} = 0.02$ Blue: $A_C^{\text{new}} = 0.04$ Green: $A_C^{\text{new}} = 0.06$

Conclusions

The FB asymmetry is the only hint of new physics in the top sector

☞ 81 dedicated papers this year

I've bet on the asymmetry (6 papers) and think ATLAS & CMS must bet too: give high priority to A_{FB} related signals

Many models had a brilliant but short life, others survive D0 and LHC

The experimental situation is not clear but not everything is Lost

ADDITIONAL SLIDES

The FB asymmetry at Tevatron

$A_{\rm FB}$ in $t\bar{t}$ CM frame is the top quark FB asymmetry in opening angle θ

$$A_{\rm FB} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}$$

where θ is the angle between the top quark momentum and the initial proton direction.

Also, since in CM frame $N_t(\cos\theta < 0) = N_{\bar{t}}(\cos\bar{\theta} > 0)$, it can be written as

$$A_{\rm FB} = \frac{N_t(\cos\theta > 0) - N_{\bar{t}}(\cos\bar{\theta} > 0)}{N_t(\cos\theta > 0) + N_{\bar{t}}(\cos\bar{\theta} > 0)}$$

that is, a charge asymmetry where the initial partons stay fixed

☞ do not confuse with C, charge conjugation symmetry !!!

The charge asymmetry at LHC

LHC is a *pp* collider, harder to define 'forward' and 'backward'

[but it can be done event by event, depending on boost of CM wrt LAB]

Alternatively, charge asymmetries can be defined:

- ★ t more forward than $\bar{t}$ at parton level
- ★ initial q larger momentum fraction than $\bar{q}$

→ tops larger (pseudo)rapidities in LAB frame

$$A_C = \frac{N(\Delta > 0) - N(\Delta < 0)}{N(\Delta > 0) + N(\Delta < 0)}$$

with $\Delta = |y_t| - |y_{\bar{t}}|$ (ATLAS) or $\Delta = |\eta_t| - |\eta_{\bar{t}}|$ (CMS)

Four-fermion operators, for fans

$1/\Lambda^2$: $O_{qq'}^{1133}$, O_{qq}^{3113} , O_{uu}^{3113} , $O_{ud'}^{3311}$, O_{qu}^{1331} , O_{qu}^{3113} , O_{qd}^{3113}

$1/\Lambda^4$: O_{qq}^{1133} , $O_{qq'}^{3113}$, O_{uu}^{1133} , O_{ud}^{3311} , O_{qu}^{3311} , $O_{qu'}^{1331}$, $O_{qu'}^{3113}$, $O_{qu'}^{3311}$, $O_{qd'}^{3113}$, $O_{qq\epsilon}^{1331}$, $O_{qq\epsilon}^{3311}$, $O_{qq\epsilon'}^{1331}$, $O_{qq\epsilon'}^{3311}$

$$O_{qq}^{ijkl} = \frac{1}{2}(\bar{q}_{Li}\gamma^\mu q_{Lj})(\bar{q}_{Lk}\gamma_\mu q_{Ll}) \qquad O_{qq'}^{ijkl} = \frac{1}{2}(\bar{q}_{Lia}\gamma^\mu q_{Ljb})(\bar{q}_{Lkb}\gamma_\mu q_{Lla})$$

$$O_{uu}^{ijkl} = \frac{1}{2}(\bar{u}_{Ri}\gamma^\mu u_{Rj})(\bar{u}_{Rk}\gamma_\mu u_{Rl})$$

$$O_{ud}^{ijkl} = (\bar{u}_{Ri}\gamma^\mu u_{Rj})(\bar{d}_{Rk}\gamma_\mu d_{Rl}) \qquad O_{ud'}^{ijkl} = (\bar{u}_{Ria}\gamma^\mu u_{Rjb})(\bar{d}_{Rkb}\gamma_\mu d_{Rla})$$

$$O_{qu}^{ijkl} = (\bar{q}_{Li} u_{Rj})(\bar{u}_{Rk} q_{Ll}) \qquad O_{qu'}^{ijkl} = (\bar{q}_{Lia} u_{Rjb})(\bar{u}_{Rkb} q_{Lla})$$

$$O_{qd}^{ijkl} = (\bar{q}_{Li} d_{Rj})(\bar{d}_{Rk} q_{Ll}) \qquad O_{qd'}^{ijkl} = (\bar{q}_{Lia} d_{Rjb})(\bar{d}_{Rkb} q_{Lla})$$

$$O_{qq\epsilon}^{ijkl} = (\bar{q}_{Li} u_{Rj}) \left[(\bar{q}_{Lk}\epsilon)^T d_{Rl}\right] \qquad O_{qq\epsilon'}^{ijkl} = (\bar{q}_{Lia} u_{Rjb}) \left[(\bar{q}_{Lkb}\epsilon)^T d_{Rla}\right]$$

A_{FB} with effective operators

Example: corrections to $u\bar{u} \to t\bar{t}$ in terms of the C's

$$\delta\sigma_{\mathrm{int}}^{F,B}(u\bar{u}) = \frac{D_{\mathrm{int}}^{F,B}}{\Lambda^2}\left[C_{qq'}^{1133} + C_{qq}^{3113} + C_{uu}^{3113}\right] - \frac{\tilde{D}_{\mathrm{int}}^{F,B}}{\Lambda^2}\left[C_{qu}^{1331} + C_{qu}^{3113}\right]$$

$$\begin{aligned}\delta\sigma_{\mathrm{quad}}^{F,B}(u\bar{u}) = {} & \frac{D_1^{F,B}}{\Lambda^4}\left[\Pi(C_{qq}^{1133} + C_{qq'}^{3113}, C_{qq'}^{1133} + C_{qq}^{3113}) + \Pi(C_{uu}^{1133}, C_{uu}^{3113})\right] \\ & + \frac{\tilde{D}_1^{F,B}}{\Lambda^4}\left[\Pi(C_{qu'}^{1331}, C_{qu}^{1331}) + \Pi(C_{qu'}^{3113}, C_{qu}^{3113})\right] + \frac{D_2}{\Lambda^4}\Pi(C_{qu'}^{3311}, C_{qu}^{3311}) \\ & - \frac{D_4}{\Lambda^4}\left[\Pi(C_{qq}^{1133} + C_{qq'}^{3113}, C_{qu'}^{1331}, C_{qq'}^{1133} + C_{qq}^{3113}, C_{qu}^{1331})\right. \\ & \left. + \Pi(C_{qu'}^{3113}, C_{uu}^{1133}, C_{qu}^{3113}, C_{uu}^{3113})\right]\end{aligned}$$

[C's: operator coefficients ; D's: numerical constants ; Π's: some polynomials]

Corrections up to order $1/\Lambda^4$?

For the range of parameters required to explain the asymmetry, quadratic corrections are important.

☞ remember that $A_{\text{new}} \sim A_{\text{SM}}$

However, we have to worry about consistency: dim 8 not considered!

For extra vector bosons and scalars approximation consistent because:

- for C small, Λ^4 does not matter
- for C large, SM $\times$ dim 8 $\sim C/\Lambda^4$ is subleading with respect to (dim 6)$^2 \sim C^2/\Lambda^4$.

From models to effective operators

Model X has a Z_1' (in rep $\mathcal{B}_\mu$) with mass M_1 and couplings

$$-(g_{13}^{q}\bar{u}_L\gamma^\mu t_L + g_{13}^{u}\bar{u}_R\gamma^\mu t_R + \dots)\, Z_{1\mu}' + \text{h.c.}$$

and a Z_2' (in rep $\mathcal{B}_\mu$) with mass M_2 and couplings

$$-(h_{13}^{q}\bar{u}_L\gamma^\mu t_L + h_{13}^{u}\bar{u}_R\gamma^\mu t_R + \dots)\, Z_{2\mu}' + \text{h.c.}$$

Then, you look in the tables and find the coefficients, for example

tt

$$\frac{C_{uu}^{1313}}{\Lambda^2} = -\frac{(g_{13}^u)^2}{{M_1}^2} - \frac{(h_{13}^u)^2}{{M_2}^2}, \dots$$

$t\bar{t}$

$$\frac{C_{uu}^{3113}}{\Lambda^2} = -\frac{|g_{13}^u|^2}{{M_1}^2} - \frac{|h_{13}^u|^2}{{M_2}^2}, \dots$$

from which you calculate your σ, A_{FB}, etc. Just add up!

A large asymmetry with a small $t\bar{t}$ tail

The asymmetry can be large with not too large couplings provided

$$\left.\begin{array}{l}\delta\sigma^F(u\bar{u}) = -\delta\sigma^B(u\bar{u}) \\ \delta\sigma^F(d\bar{d}) = -\delta\sigma^B(d\bar{d})\end{array}\right\} \rightarrow \quad \delta\sigma(q\bar{q} \to t\bar{t}) = 0$$

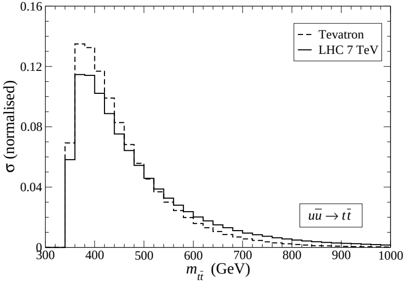
This happens at all energies provided that

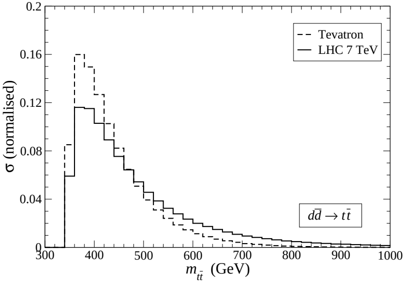
$$\begin{aligned}\left[C_{qq'}^{1133} + C_{qq}^{3113} + C_{uu}^{3113}\right] &= \left[C_{qu}^{1331} + C_{qu}^{3113}\right] \\ \left[C_{qq'}^{1133} + 2\, C_{ud'}^{3311}\right] &= \left[C_{qu}^{1331} + C_{qd}^{3113}\right]\end{aligned}$$

Looks complicated? It's automatic for an axigluon: $-g_{ii}^q = g_{ii}^u = g_{ii}^d$

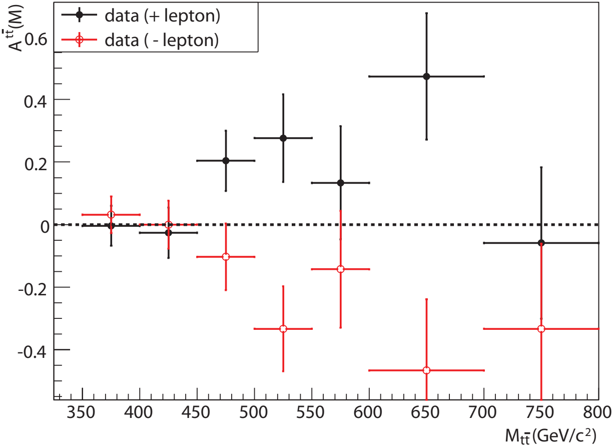
Possible in other models: necessary $LL + RR = LR + RL$ for $u\bar{u}$ and $d\bar{d}$

$t\bar{t}$ invariant mass distributions

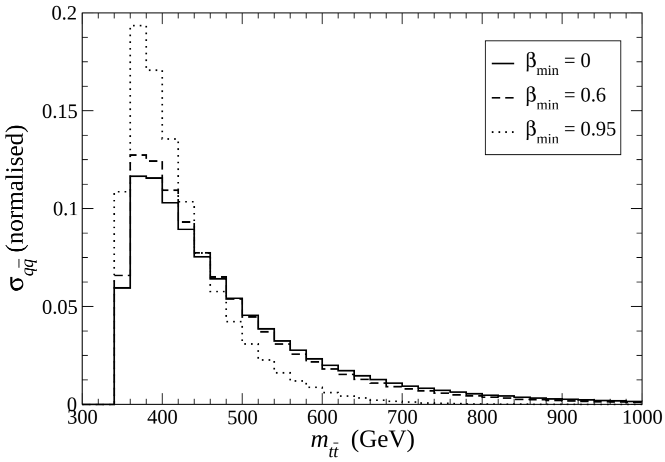




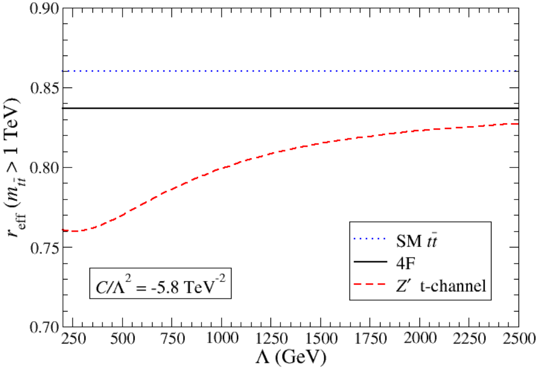
CDF Camel profile



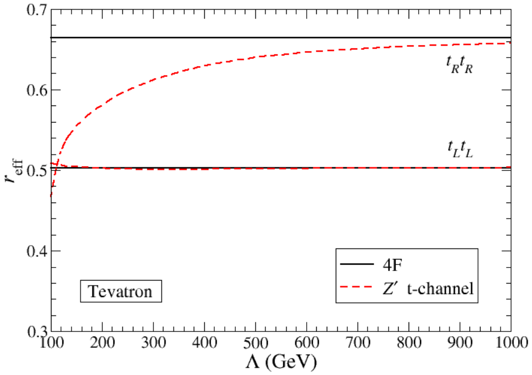
Effect of β cut on $m_{t\bar{t}}$



Efficiency at $t\bar{t}$ tail



Efficiency for *tt* at Tevatron



Efficiency for *tt* at LHC