Signals of the Tevatron $t\bar{t}$ asymmetry at LHC

J. A. Aguilar Saavedra
in collaboration with M. Pérez-Victoria

Departamento de Física Teórica y del Cosmos
Universidad de Granada

Portoroz, April 11th 2011

This talk is mainly based on papers

- JAAS, M. Pérez-Victoria, *"Probing the Tevatron $t\bar{t}$ asymmetry at LHC"*, arXiv:1103.2765
- JAAS, M. Pérez-Victoria, *"No like-sign tops at Tevatron: Constraints on extended models and implications for the $t\bar{t}$ asymmetry"*, arXiv:1104.1385

The FB asymmetry

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

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

or, since in CM frame $N_t(\cos\theta < 0) = N_{\bar{t}}(\cos\bar{\theta} > 0)$,

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

$A_{\rm FB}$ is a charge asymmetry where the initial partons stay fixed

☞ not to be confused with C, charge conjugation symmetry

QCD tree level FB symmetric [V coupling; compare with $A_{\rm FB}$ at LEP]

→ $A_{\rm FB}$ is generated at NLO in QCD

The FB asymmetry at Tevatron

Since some time there were discrepancies but in 2011 they got worse: for $m_{t\bar{t}} > 450$ GeV there are 3.4σ!

$$A_{\mathrm{FB}}^{\mathrm{SM}} = 0.088 \pm 0.013 \qquad A_{\mathrm{FB}}^{\mathrm{exp}} = 0.475 \pm 0.114$$

This is an endless source of models for theorists!

Unfortunately, models are not so easy because $\sigma = \sigma_{\mathrm{SM}}$

$\sigma(t\bar{t}) = \sigma_{\mathrm{SM}} + \delta\sigma_{\mathrm{int}} + \delta\sigma_{\mathrm{quad}}$ ☞ $\delta\sigma_{\mathrm{int}} + \delta\sigma_{\mathrm{quad}} \simeq 0$

in some models this requires a new amplitude $A_{\mathrm{new}} \sim -2A_{\mathrm{SM}}$!!!

that should have effects elsewhere ☞ $t\bar{t}$ tail at LHC 🙂

We don't know the NP (if any) and we haven't seen new resonances: working with effective operators is an excellent choice

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

→ gauge symmetry unbroken

$$\mathcal{L}_{\rm eff} = \mathcal{L}_4 + \mathcal{L}_6 + \mathcal{L}_8 + \dots$$

where

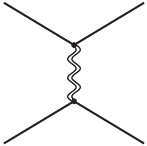
$\mathcal{L}_4 = \mathcal{L}_{\rm SM}$	→	SM Lagrangian
$\mathcal{L}_6 = \sum_x \frac{\alpha_x}{\Lambda^2} O_x$	→	O_x dim-6 gauge-invariant operators
$\mathcal{L}_8$	→	usually ignored

Here we are not doing anything new, nor modern

The history of the SM

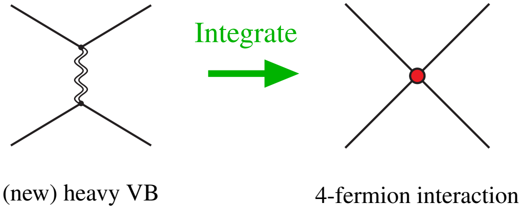
1. 1933: Fermi introduces 4F interaction to explain β decay
2. 1958: $V - A$ structure is determined { Feynman, Gell-Mann, PR 109 (1958) 193; Sudharsan, Marshak, PR 109 (1958) 1860 }
3. 1961-1968: birth of EW theory { Glashow, NP 22 (1961) 589; Weinberg, PRL 19 (1967) 1264; Salam, Proceedings (1968) }
4. 1983: UA1 and UA2 discover the W and Z at CERN

Heavy physics and 4F operators



(new) heavy VB

Heavy physics and 4F operators



$A_{\rm FB}$ in the effective framework

Studies done using effective operators are often referred to as 'model independent approach' because using them you can parameterise corrections from any decoupling heavy physics to cross sections, etc.

Example: $u\bar{u} \to t\bar{t}$, $d\bar{d} \to t\bar{t}$ and 4F operators

20 independent dim 6 operators contribute

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

$O_{qu'}^{3311}$, $O_{qd'}^{3113}$, $O_{qq\epsilon}^{1331}$, $O_{qq\epsilon}^{3311}$, $O_{qq\epsilon'}^{1331}$, $O_{qq\epsilon'}^{3311}$

[subindices label structure ; superindices are the quark flavours]

Four-fermion operators, for fans

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

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

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

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

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

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

A_{FB} with effective operators

Corrections to cross sections in terms of the C's 1008.3562

$$
\begin{aligned}
\delta\sigma^{F,B}_{\mathrm{int}}(u\bar{u}) &= \frac{D^{F,B}_{\mathrm{int}}}{\Lambda^2}\left[C^{1133}_{qq'} + C^{3113}_{qq} + C^{3113}_{uu}\right] - \frac{\tilde{D}^{F,B}_{\mathrm{int}}}{\Lambda^2}\left[C^{1331}_{qu} + C^{3113}_{qu}\right] \\
\delta\sigma^{F,B}_{\mathrm{4F}}(u\bar{u}) &= \frac{D^{F,B}_{1}}{\Lambda^4}\left[\Pi(C^{1133}_{qq} + C^{3113}_{qq'}, C^{1133}_{qq'} + C^{3113}_{qq}) + \Pi(C^{1133}_{uu}, C^{3113}_{uu})\right] \\
&\quad + \frac{\tilde{D}^{F,B}_{1}}{\Lambda^4}\left[\Pi(C^{1331}_{qu'}, C^{1331}_{qu}) + \Pi(C^{3113}_{qu'}, C^{3113}_{qu})\right] + \frac{D_2}{\Lambda^4}\,\Pi(C^{3311}_{qu'}, C^{3311}_{qu}) \\
&\quad - \frac{D_4}{\Lambda^4}\Big[\Pi(C^{1133}_{qq} + C^{3113}_{qq'}, C^{1331}_{qu'}, C^{1133}_{qq'} + C^{3113}_{qq}, C^{1331}_{qu}) \\
&\quad + \Pi(C^{3113}_{qu'}, C^{1133}_{uu}, C^{3113}_{qu}, C^{3113}_{uu})\Big]
\end{aligned}
$$

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

Seems complicated but it's easy to implement in F77 code

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

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

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

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)$^2 \sim C^2/\Lambda^4$.

A_{FB} with effective operators

This has been done in several places with several approximations

$1/\Lambda^2$: 0912.1105, 1008.3869, 1010.6304

$1/\Lambda^4$: 1008.3562, 1103.2297

BUT

We also want the ‘theory connection’.

Rembember history of the SM. We want to see which NP could be generating this, if any.

Effective operators are not the theory!

The bridge to theories

Now, which can be the "heavy new physics" in the case of $q\bar{q} \to t\bar{t}$?

- Z' or g' in $u\bar{u} \to t\bar{t}$, s and t-channel
- W' in $d\bar{d} \to t\bar{t}$, t-channel
- charge $4/3$ vector boson in $u\bar{u} \to t\bar{t}$, u-channel
- …
- and also scalars!

Fortunately, 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	$(\bar{6},3)_{-\frac{1}{3}}$
$\mathcal{Y}^1_\mu$	$(\bar{6},2)_{\frac{1}{6}}$		
$\mathcal{Y}^5_\mu$	$(\bar{6},2)_{-\frac{5}{6}}$		

Important comments

- ★ We need a different notation because, for example, a Z' can be an $\text{SU}(2)_L$ singlet $\mathcal{B}_\mu$ or belong to a triplet $\mathcal{W}_\mu$ (in SM both).
- ★ Any model will have a number of particles and multiplets in any of these representations.
- ★ For each representation we can obtain the contributions to $u\bar{u}, d\bar{d} \to t\bar{t}$ in terms of 4F operators (see next slide).
- ★ These contributions sum up linearly (more on this later).
- ★ We are considering all models. We are model-independent!

From the Lagrangian to effective operators

$$\left.\begin{array}{l}\text{couplings } g_{ij} \\ \text{masses } M\end{array}\right\} \rightarrow \text{effective operators } C\,, \quad \Lambda \equiv M$$

	C_{qq}^{3113}	$C_{qq'}^{1133}$	C_{uu}^{3113}	$C_{ud'}^{3311}$	C_{qu}^{1331}	C_{qu}^{3113}	C_{qd}^{3113}
$\mathcal{B}_\mu$	$-\|g_{13}^q\|^2$	–	$-\|g_{13}^u\|^2$	–	–	–	–
$\mathcal{W}_\mu$	$\|g_{13}\|^2$	$-2\|g_{13}\|^2$	–	–	–	–	–
$\mathcal{G}_\mu$	$\frac{1}{6}\|g_{13}^q\|^2$	$-\frac{1}{2}g_{11}^q g_{33}^q$	$\frac{1}{6}\|g_{13}^u\|^2$ $-\frac{1}{2}g_{11}^u g_{33}^u$	$-\frac{1}{4}g_{33}^u g_{11}^d$	$\frac{1}{2}g_{11}^q g_{33}^u$	$\frac{1}{2}g_{33}^q g_{11}^u$	$\frac{1}{2}g_{33}^q g_{11}^d$
$\mathcal{H}_\mu$	$-\frac{1}{6}\|g_{13}\|^2$ $-g_{11}g_{33}$	$\frac{1}{3}\|g_{13}\|^2$ $+\frac{1}{2}g_{11}g_{33}$	–	–	–	–	–
$\mathcal{B}_\mu^1$	–	–	–	$-\frac{1}{2}\|g_{13}\|^2$	–	–	–
$\mathcal{G}_\mu^1$	–	–	–	$\frac{1}{12}\|g_{13}\|^2$	–	–	–
$\mathcal{Q}_\mu^1$	–	–	–	–	–	–	$\|g_{13}\|^2$
$\mathcal{Q}_\mu^5$	–	–	–	–	$\|g_{31}\|^2$	$\|g_{13}\|^2$	–
$\mathcal{Y}_\mu^1$	–	–	–	–	–	–	$-\frac{1}{2}\|g_{13}\|^2$
$\mathcal{Y}_\mu^5$	–	–	–	–	$-\frac{1}{2}\|g_{31}\|^2$	$-\frac{1}{2}\|g_{13}\|^2$	

The bridge to theories: how to

Model X has a Z'_1 (in rep $\mathcal{B}_\mu$) with mass M_1 and couplings

$$-\left(g_{13}^q \bar u_L \gamma^\mu t_L + g_{13}^u \bar u_R \gamma^\mu t_R + \dots\right) Z'_{1\mu} + \text{h.c.}$$

and a Z'_2 (in rep $\mathcal{B}_\mu$) with mass M_2 and couplings

$$-\left(h_{13}^q \bar u_L \gamma^\mu t_L + h_{13}^u \bar u_R \gamma^\mu t_R + \dots\right) Z'_{2\mu} + \text{h.c.}$$

Then, you look in the tables and find the coefficients

$$\frac{C_{uu}^{1313}}{\Lambda^2} = -\frac{(g_{13}^u)^2}{{M_1}^2} - \frac{(h_{13}^u)^2}{{M_2}^2}\,, \quad \frac{C_{uu}^{3113}}{\Lambda^2} = -\frac{|g_{13}^u|^2}{{M_1}^2} - \frac{|h_{13}^u|^2}{{M_2}^2}\,, \quad \dots$$

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

Constraints on popular models

Many popular models explaining $A_{\rm FB}$ fall into one of these classes ...

- Z' in t-channel
- W' in t-channel
- scalar sextets or triplets in u-channel
- g' in s- and/or t-channels

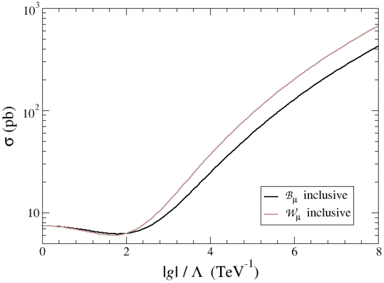
... and, in any case, combinations are straightforward to discuss once the contributions from <u>all</u> representations are known

Example #1: Z' (t channel)

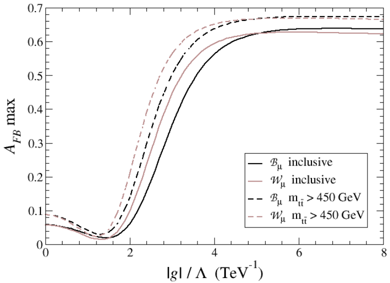
Large cancellation $A_{\text{new}} \sim -2A_{\text{SM}}$ required to fit σ and A_{FB}

Large coupling $g \sim 2.5$ TeV^{-1} [$1/\Lambda^4$ required]

σ at Tevatron



A_{FB} at Tevatron



Notice that at order $1/\Lambda^2$ σ and A_{FB} are reduced 1010.6304

For a *single* Z' boson, this implies like-sign tt production

$$\begin{aligned}\sigma(tt) &= \frac{E_1}{\Lambda^4}\left[|C_{qq}^{1313}+C_{qq'}^{1313}|^2+|C_{uu}^{1313}|^2\right]\\ &+\frac{E_2}{\Lambda^4}\left[|C_{qu'}^{1313}|^2+|C_{qu}^{1313}|^2+\tfrac{2}{3}\,\mathrm{Re}\,C_{qu'}^{1313}C_{qu}^{1313*}\right]\\ &+\frac{E_3}{\Lambda^4}\left\{\mathrm{Re}\,C_{qu'}^{1313}C_{qu}^{1313*}+\tfrac{1}{6}\left[|C_{qu'}^{1313}|^2+|C_{qu}^{1313}|^2\right]\right\}\end{aligned}$$

No model-independent relation between tt and $t\bar{t}$. Independent operators!

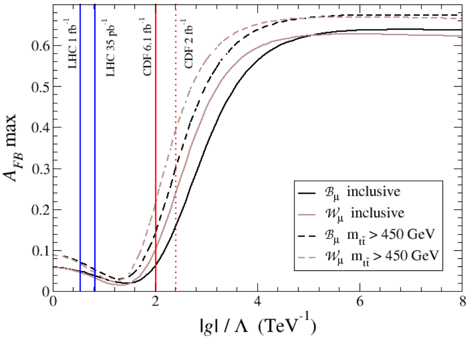
Plug $\mathcal{B}_\mu$ into effective operators

$A_{\rm FB}$	$\sigma(tt)$
$C_{qq}^{3113}=-|g_{13}^q|^2$	$C_{qq}^{1313}=-(g_{13}^q)^2$
$C_{uu}^{3113}=-|g_{13}^u|^2$	$C_{uu}^{1313}=-(g_{13}^u)^2$
$\ldots$	$\ldots$

→ $A_{\rm FB}$ related to $\sigma(tt)$

New CDF limit on like-sign tt with 6.1 fb^{-1} CDF note 10466, 07/04/11

excludes models with a *heavy* Z' contributing sizeably to A_{FB}

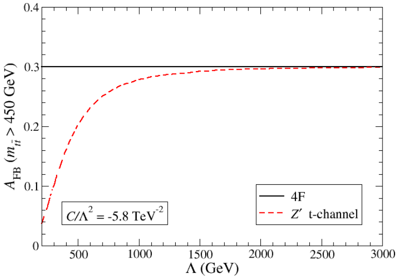


However … cunning physicists build models with light elusive particles hard to see anywhere but in $t\bar{t}$ production …

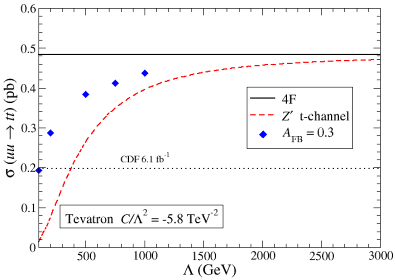
For t-channel new physics, effective operators overestimate A_{FB} and $\sigma(tt)$

☞ models with $M_{Z'} \lesssim 200$ GeV still viable

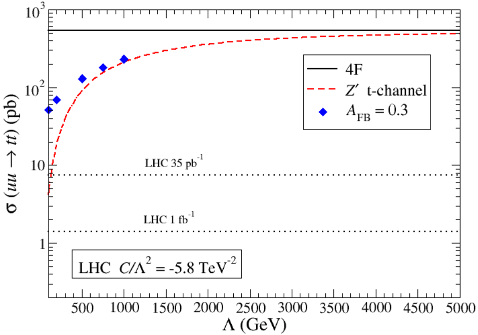
A_{FB} at Tevatron



$\sigma(tt)$ at Tevatron



In any case, models with a t-channel Z' can be probed and eventually excluded with 2010 LHC data



still one possible escape: introduce more than one Z' 1103.4835

[two degenerate Z' with couplings differing by i give no contribution to tt]

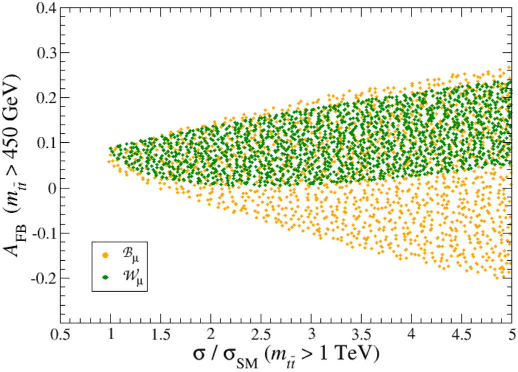
BUT

one probe from which you cannot escape is $t\bar{t}$ production itself:

- ★ if you have something anomalous in $t\bar{t}$ at Tevatron
- ★ something anomalous in $t\bar{t}$ must be seen at LHC

The best candidate is the $t\bar{t}$ tail: $\left\{ \begin{array}{l} \text{not dominated by } gg \to tt \\ \text{more sensitive to heavy physics} \end{array} \right.$

Arbitrary *heavy Z′* (*s* and *t* channels)



$A_{FB} \simeq 0.28$ implies $5\times$ tail above 1 TeV for LHC

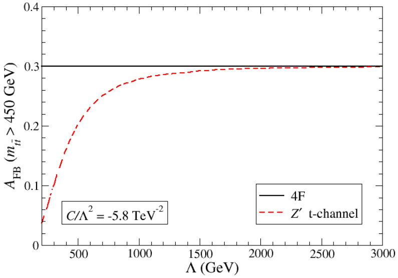
→ excess should have been already seen

… and for lighter Z' …

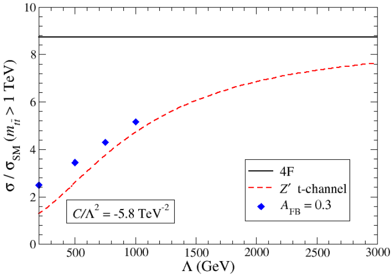
For light t-channel Z', effective operators overestimate A_{FB} and tail

☞ more luminosity needed to see or exclude

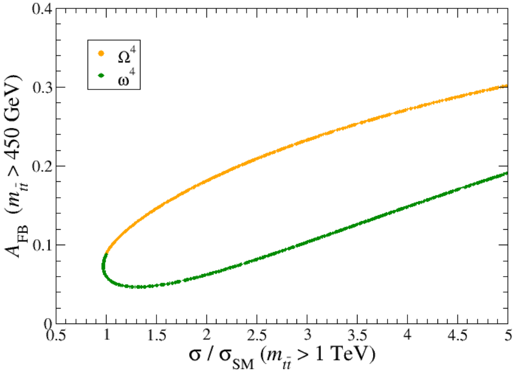
A_{FB} at Tevatron



tail at LHC

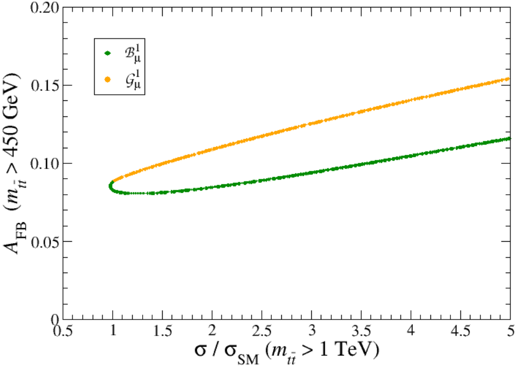


Example #2: colour-sextet and triplet scalars



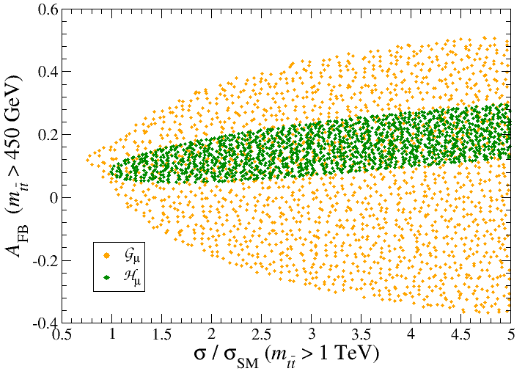
$A_{FB} \simeq 0.3$ implies $5\times$, $8\times$ tail above 1 TeV at LHC

Example #3: W' in t-channel



$A_{FB} \simeq 0.3$ implies $19\times$, $25\times$ tail above 1 TeV at LHC

Example #4: g'



$A_{FB} \simeq 0.3$ with $1.5\times$ tail → testable in near future

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

The asymmetry can be large with not too large couplings provided

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

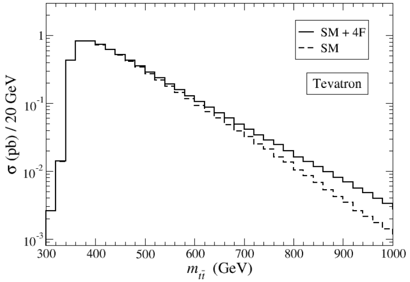
This happens <u>at all energies</u> provided that

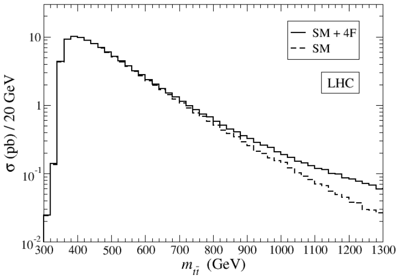
$$\begin{aligned} \left[C_{qq'}^{1133} + C_{qq}^{3113} + C_{uu}^{3113}\right] &= \left[C_{qu}^{1331} + C_{qu}^{3113}\right] \\ \left[C_{qq'}^{1133} + 2\,C_{ud'}^{3311}\right] &= \left[C_{qu}^{1331} + C_{qd}^{3113}\right] \end{aligned}$$

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 $d\bar{d}$

Tails corresponding to $A_{FB} = 0.366$ (best fit)





Tevatron

$1.5\times$ tail above 700 GeV

(within exp. error)

LHC

$2.3\times$ tail above 1 TeV

testable soon?

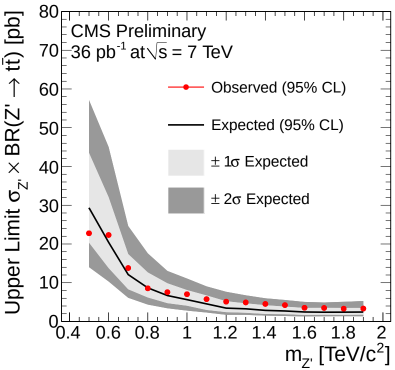
The $t\bar{t}$ tail at LHC is a crucial test

Already with 2010 data it may exclude* many models:

- Z'
- W'
- colour-triplet scalar ω^4
- colour-sextet scalar Ω^4
- colour-sextet isodoublet scalar Σ
- …

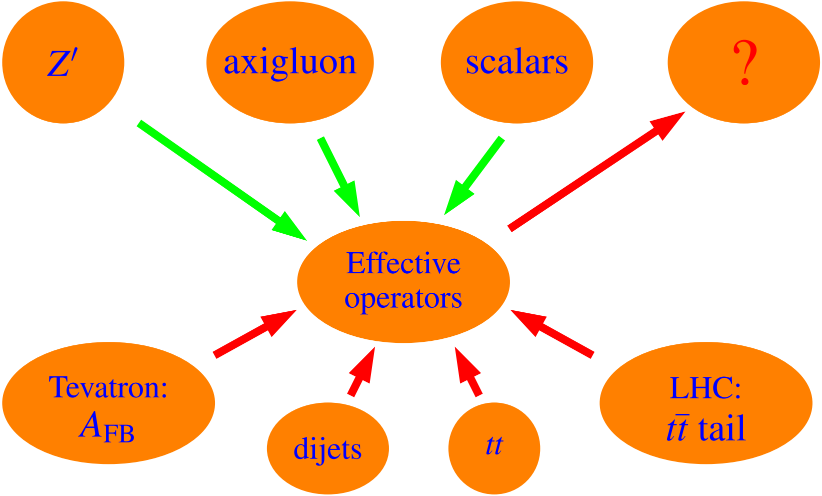
* unless the new physics is very light

CMS public data (ATLAS not public yet)



If $A_{\rm FB}$ is due to new physics, we should see enhanced $t\bar{t}$ tail at LHC. Data start to prefer a large tail but not a huge one. A careful analysis is compulsory!

Summary

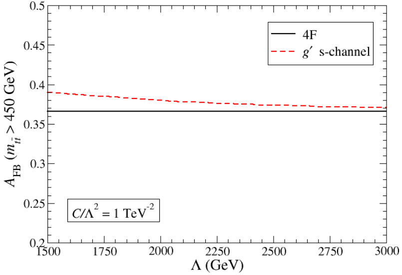

Z'
axigluon
scalars
?
Effective operators
Tevatron: A_{FB}
dijets
tt
LHC: $t\bar{t}$ tail

Additional Slides

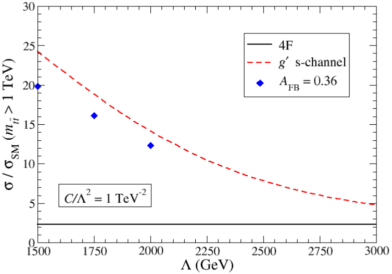
Models with *s*-channel resonances

For *s*-channel new physics, effective operators underestimate tail at LHC: effects can be much larger …

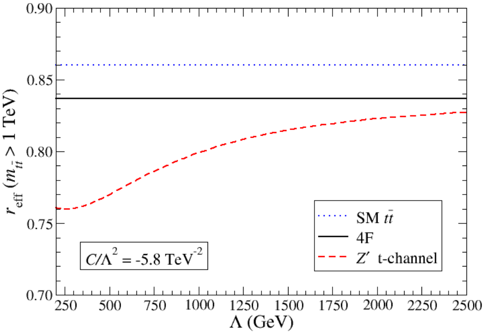
A_{FB} at Tevatron



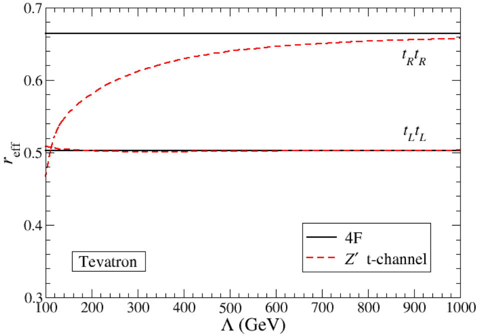
tail at LHC



Efficiency at $t\bar{t}$ tail



Efficiency for tt at Tevatron



Efficiency for tt at LHC