Flavour and the Tevatron $t\bar{t}$ asymmetry

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

Departamento de Física Teórica y del Cosmos
Universidad de Granada

FLASY2011, Valencia, July 13th 2011

This talk is mainly based on papers

- JAAS, M. Pérez-Victoria, *"Probing the Tevatron $t\bar{t}$ asymmetry at LHC"*, arXiv:1103.2765, JHEP
- 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, PLB
- JAAS, M. Pérez-Victoria, *"Asymmetries in $t\bar{t}$ production: LHC versus Tevatron"*, arXiv:1105.4606
- JAAS, M. Pérez-Victoria, *"Simple models for the top asymmetry: constraints and predictions"*, arXiv:1107.0841
- JAAS, M. Pérez-Victoria, *"Shaping the top asymmetry"*, arXiv:1107.2120 (today)

Disclaimer

This talk was intended to deal primarily with flavour aspects

In the meantime ($\sim$ 2 months), most models with non-trivial flavour are about to be excluded [as I shall show]

Then ☞ overview of models, with flavour but not much

The FB asymmetry at Tevatron

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

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

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

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

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

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

The FB asymmetry at Tevatron

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

→ $A_{\rm FB}$ is generated at NLO in QCD — Halzen et al. PLB '87, Kuhn & Rodrigo PRD '99

Electroweak contributions also known — Bernreuther & Si, NPB '10

... and NNLL corrections from soft gluon emission — Ahrens et al '11

Since some time there were discrepancies but in 01/2011 they got worse: for $m_{t\bar{t}} > 450$ GeV there are 3.4σ!

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

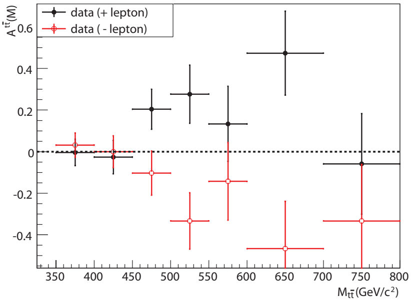
→ $0.11^{+1.7}_{-0.9}$ [06/11]

The FB asymmetry at Tevatron

$q\bar{q} \to t\bar{t}$ dominates at Tevatron, large $A_{\rm FB}$ suggests new physics here

This is an endless source of models for theorists!

One plot to warm up ...



CDF ’11

$A_{\rm FB}$ as a function of $m_{t\bar{t}}$

The excess does not seem only statistical

☞ unknown systematics ...
... or new physics!

This $A_{\rm FB}$ excess explains a large $O(70)$ paper excess since 01/2011

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

A_{FB} beyond the SM

Unfortunately, building models is not easy if $\sigma_{SM} = \sigma_{exp}$

$\sigma_{SM} = 7.46^{+0.66}_{-0.80}$ pb Langenfeld et al PRD'09

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

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

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

BUT

it is also possible that $\sigma_{SM} < \sigma_{exp}$

$\sigma_{SM} = 6.30 \pm 0.19^{+0.31}_{-0.23}$ pb Ahrens et al JHEP'10

in which case moderate contributions to σ and A_{FB} would be natural

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

[large A_{FB} suggests new physics at tree level]

- 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 $\text{SU}(3) \times \text{SU}(2)_L \times \text{U}(1)_Y$ 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	$(\bar{6},3)_{-\frac{1}{3}}$
$\mathcal{Y}^1_\mu$	$(\bar{6},2)_{\frac{1}{6}}$		
$\mathcal{Y}^5_\mu$	$(\bar{6},2)_{-\frac{5}{6}}$		

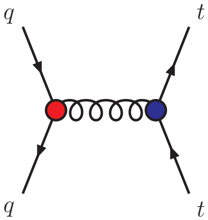
Important comments

- ★ A different notation is needed because, for example, a Z' can be an $\mathrm{SU}(2)_L$ singlet $\mathcal{B}_\mu$ or belong to a triplet $\mathcal{W}_\mu$ (in SM both).
- ★ A model can have a number of particles and multiplets in any of these representations.
- ★ 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 !!!

s-channel

Example: 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)

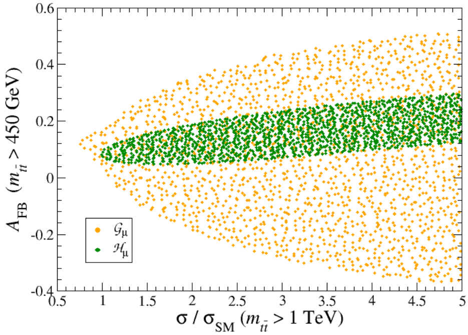
larger coupling to tt natural in extra dimensions

Djouadi et al. PRD '10
Álvarez et al. JHEP '11
Barceló et al. '11

Distinctive signature: peak (bump) in the $m_{t\bar{t}}$ distribution

Peak not seen → make it higher!

… but for $M \gg \sqrt{\hat{s}}$: enhanced $t\bar{t}$ tail, especially at LHC



JAAS & MPV JHEP'11

Heavy $\mathcal{G}_\mu$

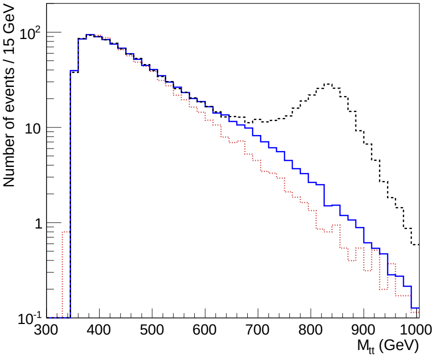
Arbitrary couplings

x axis: tail enhancement
y axis: A_{FB} at Tevatron

→ $A_{FB} = 0.3$ implies $1.5\times$ tail

s-channel

… or … peak not seen ➙ make it broader!



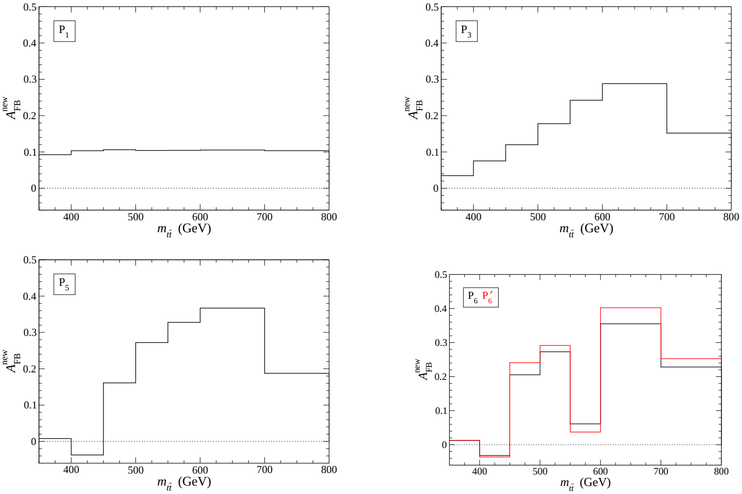
Barceló et al. ’11

$M = 850$ GeV
$\Gamma = 0.7\,M$

$g_L^q = 0.3g \;\; g_R^q = -0.3g$
$g_L^t = 0 \;\; g_R^t = 4.0g$

$+$ new quark U

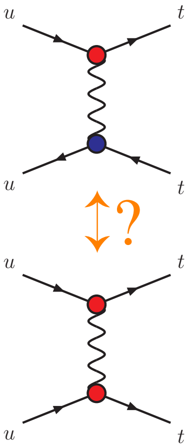
s-channel gluons allow for different asymmetry profiles



JAAS & MPV 'today

t-channel

Example: neutral vector boson Z' ($\mathcal{B}_\mu$)



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

In this case, a distinctive signature is tt production at LHC

Jung et al. PRD'10
Cao et al. PRD'10
Berger et al. PRL'11

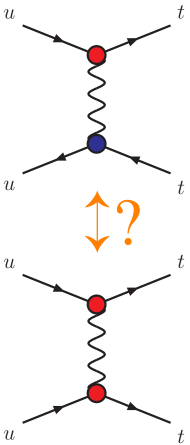
but tight limits already from Tevatron

JAAS & MPV PLB'11
CDF note 10466

and now from LHC CMS '11

t-channel

Example: neutral vector boson Z' ($\mathcal{B}_\mu$)



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

A *complex* Z': two real degenerate Z'_1, Z'_2 with couplings differing by i

☞ like Dirac vs Majorana neutrinos!

Natural with extended flavour symmetries

Jung et al. '11

t-channel

Additional feature / problem: large $t\bar{t}$ tail at LHC

① Interference $Z' -$ SM is *negative*: it decreases A_{FB}

② A positive contribution to A_{FB} and agreement with Tevatron $\sigma(t\bar{t})$ require large coupling and cancellation with SM amplitude

☞ This implies a large $t\bar{t}$ tail at LHC

agreement with Tevatron $\sigma(tt)$	✔
positive contribution to A_{FB}	✔
tail $\leq 3 \times$ SM for $m_{t\bar{t}} > 1$ TeV	✔

→ $M_{Z'} \leq 360$ GeV

Interlude: linear vs quadratic new physics

These two examples motivate a classification

- *'Linear'* new physics: quadratic NP contributions <u>not</u> essential

  Coupling can go to zero keeping agreement with total $\sigma(t\bar{t})$

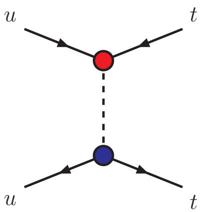
- *'Quadratic'* new physics: quadratic contributions <u>essential</u>

  Large cancellation, parameter space disconnected from SM

  ☞ easily disfavoured (excluded) by LHC data !!!

u-channel

Example: colour-sextet Ω^4 / triplet 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 …

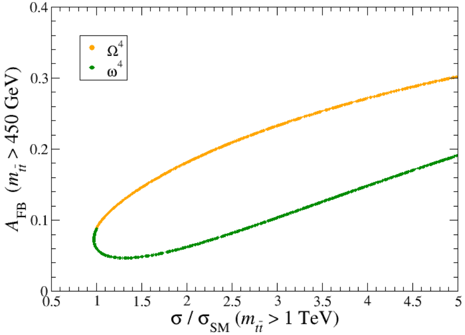
Grinstein et al. PRL '11

Ligeti et al. JHEP '11

ω^4 flavour-antisymmetric couplings

u-channel

Enhanced $t\bar{t}$ tail at LHC, especially for heavy masses



JAAS & MPV JHEP'11

Heavy Ω^4 / ω^4

Arbitrary couplings

x axis: tail enhancement
y axis: A_{FB} at Tevatron

→ $A_{FB} = 0.3$ implies $> 5\times$ tail

u-channel

Additional feature / problem

The contribution to A_{FB} is negative for small Ω^4 / ω^4 masses

☞ *u*-channel propagator prefers *backward* tops !!!

Numerator does not, however

Masses $\gtrsim$ 220 GeV required for positive A_{FB} at Tevatron

☞ But going to high m_{tt} you will finally 'see' *u*-channel propagator

. . . interesting . . . 🙂

no-channel: effective framework

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

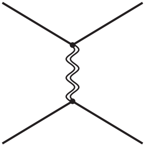
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_6 + \ldots \qquad \mathcal{L}_6 = \sum_x \frac{\alpha_x}{\Lambda^2} O_x$$

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.

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

☞ But note that direct calculation & effective operators tell us that a Z' explaining A_{FB} must be light

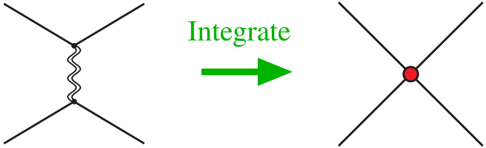
Heavy physics and 4F operators



(new) heavy VB

couplings g_{ij}
masses M $\Bigg\}$ → effective operators C , $\Lambda \equiv M$

Heavy physics and 4F operators



(new) heavy VB

4-fermion interaction

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

4F operators for $u\bar{u} \to t\bar{t}$ and $d\bar{d} \to t\bar{t}$

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

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

[subindices label structure ; superindices are the quark flavours]

This has been done in several places with several approximations

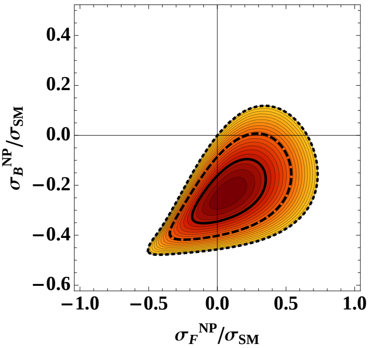
$1/\Lambda^2$:

Jung et al. PLB'10
Zhang & Willenbrock PRD'11
Degrande et al. JHEP'11
[interference with SM]

$1/\Lambda^4$:

JAAS NPB'11
Delaunay et al. '11
JAAS & MPV JHEP'11
[quadratic in NP]

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



Grinstein et al PRL ’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

del Aguila et al. JHEP'10

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

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

unless you don't want them to

Interfering operators – scalars

JAAS & MPV JHEP'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

The issue is not whether NP interferes but *how* it does

1. Z', W', ω^4: negative, decreases $A_{\rm FB}$ and σ
2. Ω^4: positive, increases $A_{\rm FB}$ and σ
3. axi-$\mathcal{G}_\mu$: $\delta\sigma^F = -\delta\sigma^B$, increases $A_{\rm FB}$ keeping σ at $1/\Lambda^2$

Signals at LHC

Cunning physicists build models with (often light) elusive particles hard to see anywhere but in the $t\bar{t}$ asymmetry …

BUT

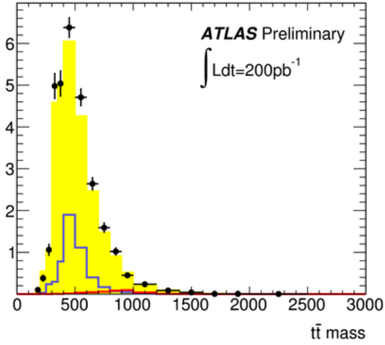
one probe from which you cannot escape is $t\bar{t}$ production itself:

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

Excellent candidate: the $t\bar{t}$ tail: $\begin{cases} \text{not dominated by } gg \to tt \\ \text{more sensitive to heavy physics} \end{cases}$

and, of course, the charge asymmetry A_C at LHC

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



ATLAS ’11

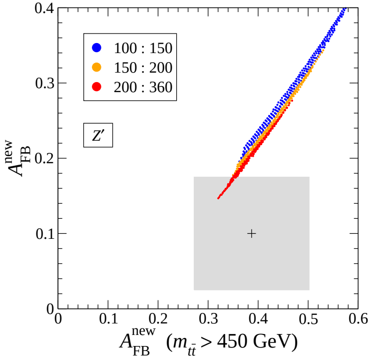
Implications of tail $\leq 3 \times$ SM

[tail $\equiv m_{t\bar{t}} \geq 1$ TeV]

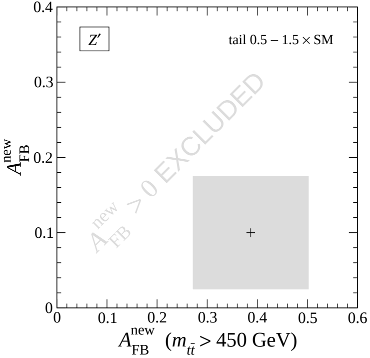
- Z': $M \leq 360$ GeV
- W': $M \leq 2.2$ TeV
- axigluon & axi-friends: small tail if heavy
- Ω^4: tail less constraining than Tevatron σ
- ω^4: $M \leq 1.9$ TeV

Example: Z'

tail $\leq 3 \times$ SM



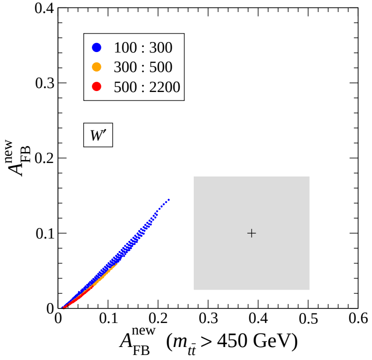
tail $0.5 - 1.5 \times$ SM



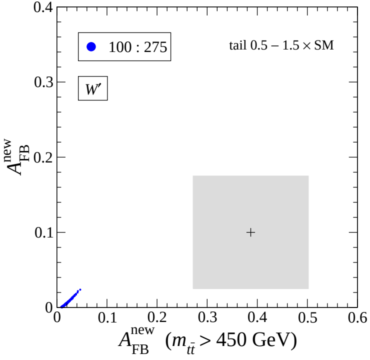
JAAS & MPV ’11

Example: W'

tail $\leq 3 \times$ SM



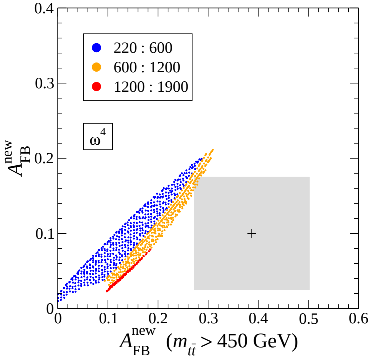
tail $0.5 - 1.5 \times$ SM



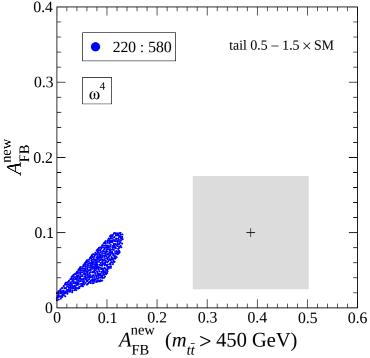
JAAS & MPV ’11

Example: ω^4

tail $\leq 3 \times$ SM



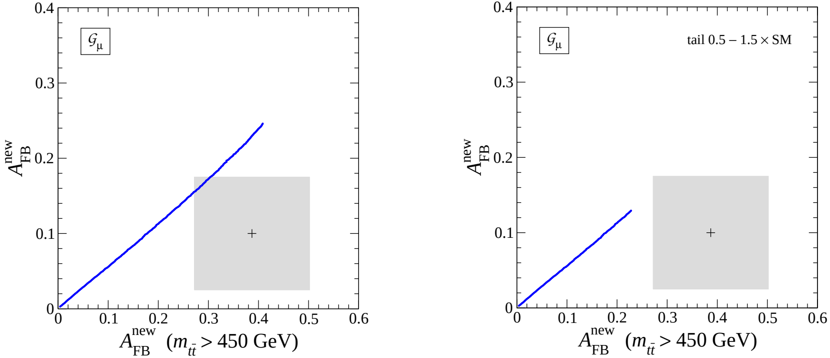
tail $0.5 - 1.5 \times$ SM



JAAS & MPV ’11

Example: heavy axigluon

tail $\leq 3 \times$ SM | tail $0.5 - 1.5 \times$ SM



JAAS & MPV '11

… and the charge asymmetry too!

CMS measurement for 35 pb^{-1}

$$A_C = 0.060 \pm 0.134\,(\text{stat}) \pm 0.026\,(\text{syst})$$

offers good hope for the (7 TeV) future:

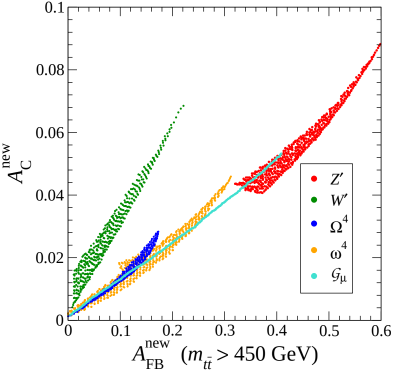
- 40% systematics will improve with more data
- statistics much larger, 1 fb^{-1} available!

☞ comparison with Tevatron A_{FB} for model discrimination

For this, a comprehensive scan over masses and couplings is required

[most papers only select few $O(2)$ benchmark points]

A_{FB} at Tevatron vs A_C at LHC



JAAS & MPV '11

A_C inclusive

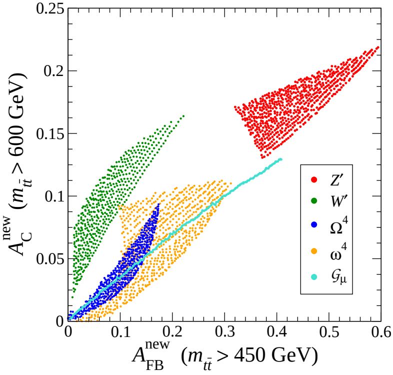
W' slope $2\times$: $d\bar{d}$ / $u\bar{u}$ PDF enhancement at LHC

Rest of models more similar

Notice that $A_C \geq 0.04$ for Z'

Tevatron: $A_{FB}^{new} = 0.387 \pm 0.115$

A_{FB} at Tevatron vs A_C at LHC



JAAS & MPV '11

A_C for $m_{t\bar{t}} > 600$ GeV

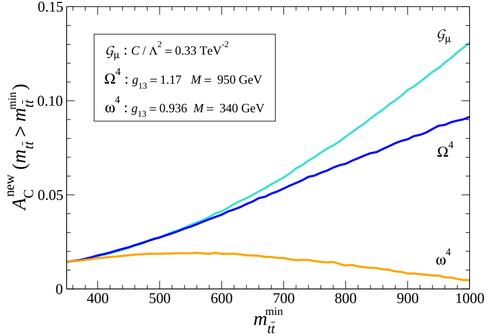
Z' (t channel) gets a boost

Ω^4 and ω^4 regions wider: larger differences between light and heavy scalars

Tevatron: $A_{FB}^{new} = 0.387 \pm 0.115$

A_{FB} at Tevatron vs A_C at LHC

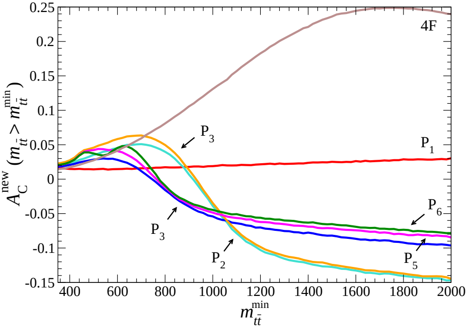
But notice that close points are not mapped close !!!



JAAS & MPV '11

$\mathcal{G}_\mu$: 4-fermion operators
Ω^4: $M = 950$ GeV
ω^4: $M = 340$ GeV

Different Tevatron profiles → also different at LHC



JAAS & MPV 'today

Distinctive feature:

Negative asymmetry at LHC reach!

What about other charge asymmetries?

Other definitions in the market too …

'Central' charge asymmetry — Ferrario & Rodrigo PRD'08

$$A_{\text{cen}} = \frac{N_t(|y| < y_0) - N_{\bar{t}}(|y| < y_0)}{N_t(|y| < y_0) + N_{\bar{t}}(|y| < y_0)}$$

'Forward' charge asymmetry — Hewett et al. '11

$$A_{\text{fwd}} = \frac{N_t(y_0 < |y| < y_1) - N_{\bar{t}}(y_0 < |y| < y_1)}{N_t(y_0 < |y| < y_1) + N_{\bar{t}}(y_0 < |y| < y_1)}$$

with y_0, y_1 some fixed (arbitrary) numbers

What about other charge asymmetries?

Comparison

Model	A_C^{new}	$A_C^{new} \times \sqrt{\sigma}$	A_{cen}^{new}	$A_{cen}^{new} \times \sqrt{\sigma}$	A_{fwd}^{new}	$A_{fwd}^{new} \times \sqrt{\sigma}$
Z'	0.0403	13.0 fb$^{1/2}$	-0.0207	-8.6 fb$^{1/2}$	0.107	19.6 fb$^{1/2}$
W'	0.0536	18.0 fb$^{1/2}$	-0.0249	-10.8 fb$^{1/2}$	0.119	23.5 fb$^{1/2}$
$\mathcal{G}_\mu$	0.0433	14.2 fb$^{1/2}$	-0.0142	-6.0 fb$^{1/2}$	0.0800	14.3 fb$^{1/2}$
ϕ	0.0242	7.7 fb$^{1/2}$	-0.0074	-3.1 fb$^{1/2}$	0.0430	7.4 fb$^{1/2}$
ω^4	0.0248	8.3 fb$^{1/2}$	-0.0085	-3.7 fb$^{1/2}$	0.0480	8.8 fb$^{1/2}$
Ω^4	0.0185	6.1 fb$^{1/2}$	-0.0060	-2.6 fb$^{1/2}$	0.0331	6.1 fb$^{1/2}$

What about other charge asymmetries?

Comparison

Model	A_C^{new}	$A_C^{new} \times \sqrt{\sigma}$	A_{cen}^{new}	$A_{cen}^{new} \times \sqrt{\sigma}$	A_{fwd}^{new}	$A_{fwd}^{new} \times \sqrt{\sigma}$
Z'	0.0403	13.0 fb$^{1/2}$	-0.0207	-8.6 fb$^{1/2}$	0.107	19.6 fb$^{1/2}$
W'	0.0536	18.0 fb$^{1/2}$	-0.0249	-10.8 fb$^{1/2}$	0.119	23.5 fb$^{1/2}$
$\mathcal{G}_\mu$	0.0433	14.2 fb$^{1/2}$	-0.0142	-6.0 fb$^{1/2}$	0.0800	14.3 fb$^{1/2}$
ϕ	0.0242	7.7 fb$^{1/2}$	-0.0074	-3.1 fb$^{1/2}$	0.0430	7.4 fb$^{1/2}$
ω^4	0.0248	8.3 fb$^{1/2}$	-0.0085	-3.7 fb$^{1/2}$	0.0480	8.8 fb$^{1/2}$
Ω^4	0.0185	6.1 fb$^{1/2}$	-0.0060	-2.6 fb$^{1/2}$	0.0331	6.1 fb$^{1/2}$

What about other charge asymmetries?

Comparison

Model	A_C^{new}	$A_C^{new} \times \sqrt{\sigma}$	A_{cen}^{new}	$A_{cen}^{new} \times \sqrt{\sigma}$	A_{fwd}^{new}	$A_{fwd}^{new} \times \sqrt{\sigma}$
Z'	0.0403	13.0 $fb^{1/2}$	-0.0207	-8.6 $fb^{1/2}$	0.107	19.6 $fb^{1/2}$
W'	0.0536	18.0 $fb^{1/2}$	-0.0249	-10.8 $fb^{1/2}$	0.119	23.5 $fb^{1/2}$
$\mathcal{G}_\mu$	0.0433	14.2 $fb^{1/2}$	-0.0142	-6.0 $fb^{1/2}$	0.0800	14.3 $fb^{1/2}$
ϕ	0.0242	7.7 $fb^{1/2}$	-0.0074	-3.1 $fb^{1/2}$	0.0430	7.4 $fb^{1/2}$
ω^4	0.0248	8.3 $fb^{1/2}$	-0.0085	-3.7 $fb^{1/2}$	0.0480	8.8 $fb^{1/2}$
Ω^4	0.0185	6.1 $fb^{1/2}$	-0.0060	-2.6 $fb^{1/2}$	0.0331	6.1 $fb^{1/2}$

What about other charge asymmetries?

Comparison

Model	A_C^{new}	$A_C^{new} \times \sqrt{\sigma}$	A_{cen}^{new}	$A_{cen}^{new} \times \sqrt{\sigma}$	A_{fwd}^{new}	$A_{fwd}^{new} \times \sqrt{\sigma}$
Z'	0.0403	13.0 $fb^{1/2}$	-0.0207	-8.6 $fb^{1/2}$	0.107	19.6 $fb^{1/2}$
W'	0.0536	18.0 $fb^{1/2}$	-0.0249	-10.8 $fb^{1/2}$	0.119	23.5 $fb^{1/2}$
$\mathcal{G}_\mu$	0.0433	14.2 $fb^{1/2}$	-0.0142	-6.0 $fb^{1/2}$	0.0800	14.3 $fb^{1/2}$
ϕ	0.0242	7.7 $fb^{1/2}$	-0.0074	-3.1 $fb^{1/2}$	0.0430	7.4 $fb^{1/2}$
ω^4	0.0248	8.3 $fb^{1/2}$	-0.0085	-3.7 $fb^{1/2}$	0.0480	8.8 $fb^{1/2}$
Ω^4	0.0185	6.1 $fb^{1/2}$	-0.0060	-2.6 $fb^{1/2}$	0.0331	6.1 $fb^{1/2}$

Conclusion: A_C is as good as A_{fwd} / A_{cen} for most models
in particular for the models surviving the tail constraints

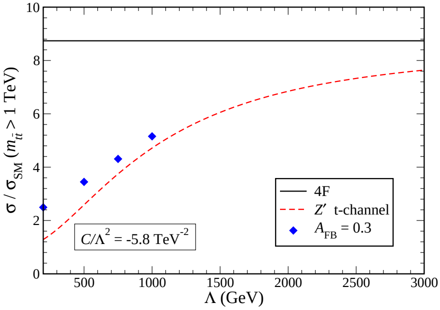
Conclusions

- ★ I hope I have convinced you that A_{FB} is an interesting hint of NP
- ★ Both CDF and D0 have been seeing positive excesses in the last few years. This might be indeed a signal of new physics
- ★ Many models have been proposed to explain the measurement
- ★ LHC will have a word on it, through the measurement of the $t\bar{t}$ tail and the charge asymmetry.
- ★ Strong motivation for the measurement of A_{C} as a function of $m_{t\bar{t}}$

Additional Slides

t-channel

High mass tail ($m_{t\bar{t}} > 1$ TeV) vs Z' mass



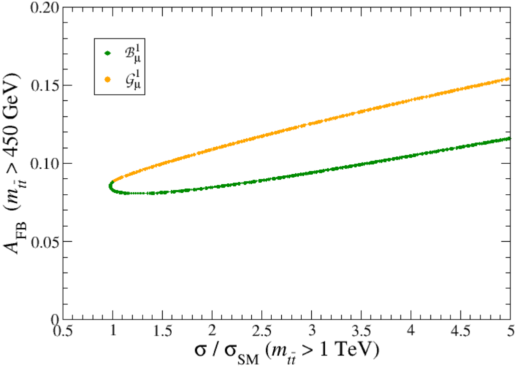
JAAS & MPV JHEP'11

tail for $A_{\rm FB} = 0.3$

x axis: Z' mass
y axis: tail enhancement

black: 4F limit
blue: exact calculation
red: fixed C/Λ^2 ($A_{\rm FB} < 0.3$)

t-channel – heavy W'



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

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

From models to effective operators

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

$$-(g^q_{13}\bar{u}_L\gamma^\mu t_L + g^u_{13}\bar{u}_R\gamma^\mu t_R + \dots)\, Z'_{1\mu} + \text{h.c.}$$

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

$$-(h^q_{13}\bar{u}_L\gamma^\mu t_L + h^u_{13}\bar{u}_R\gamma^\mu t_R + \dots)\, Z'_{2\mu} + \text{h.c.}$$

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

tt

$$\frac{C^{1313}_{uu}}{\Lambda^2} = -\frac{(g^u_{13})^2}{{M_1}^2} - \frac{(h^u_{13})^2}{{M_2}^2}, \dots$$

$t\bar{t}$

$$\frac{C^{3113}_{uu}}{\Lambda^2} = -\frac{|g^u_{13}|^2}{{M_1}^2} - \frac{|h^u_{13}|^2}{{M_2}^2}, \dots$$

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

Four-fermion operators, for fans

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

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

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

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

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

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

$A_{\rm FB}$ with effective operators

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

$$
\begin{aligned}
\delta\sigma_{\rm int}^{F,B}(u\bar{u}) &= \frac{D_{\rm int}^{F,B}}{\Lambda^2}\left[C_{qq'}^{1133} + C_{qq}^{3113} + C_{uu}^{3113}\right] - \frac{\tilde{D}_{\rm int}^{F,B}}{\Lambda^2}\left[C_{qu}^{1331} + C_{qu}^{3113}\right] \\
\delta\sigma_{\rm 4F}^{F,B}(u\bar{u}) &= \frac{D_1^{F,B}}{\Lambda^4}\left[\Pi(C_{qq}^{1133} + C_{qq'}^{3113}, C_{qq'}^{1133} + C_{qq}^{3113}) + \Pi(C_{uu}^{1133}, C_{uu}^{3113})\right] \\
&+ \frac{\tilde{D}_1^{F,B}}{\Lambda^4}\left[\Pi(C_{qu'}^{1331}, C_{qu}^{1331}) + \Pi(C_{qu'}^{3113}, C_{qu}^{3113})\right] + \frac{D_2}{\Lambda^4}\Pi(C_{qu'}^{3311}, C_{qu}^{3311}) \\
&- \frac{D_4}{\Lambda^4}\left[\Pi(C_{qq}^{1133} + C_{qq'}^{3113}, C_{qu'}^{1331}, C_{qq'}^{1133} + C_{qq}^{3113}, C_{qu}^{1331})\right. \\
&\left. + \Pi(C_{qu'}^{3113}, C_{uu}^{1133}, C_{qu}^{3113}, C_{uu}^{3113})\right]
\end{aligned}
$$

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

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

The asymmetry can be large with not too large couplings provided

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

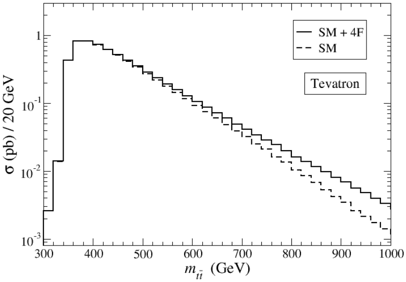
This happens <u>at all energies</u> provided that

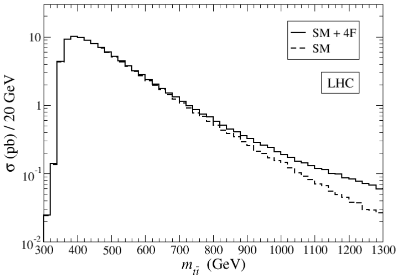
$$\begin{aligned} \left[C_{qq'}^{1133} + C_{qq}^{3113} + C_{uu}^{3113}\right] &= \left[C_{qu}^{1331} + C_{qu}^{3113}\right] \\ \left[C_{qq'}^{1133} + 2\,C_{ud'}^{3311}\right] &= \left[C_{qu}^{1331} + C_{qd}^{3113}\right] \end{aligned}$$

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

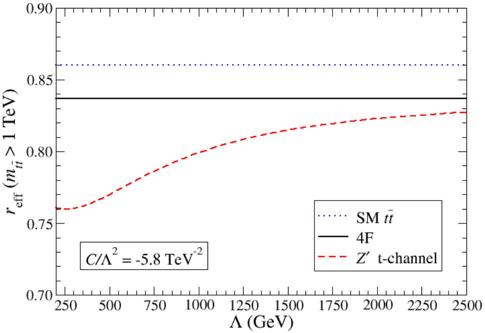
(within exp. error)

LHC

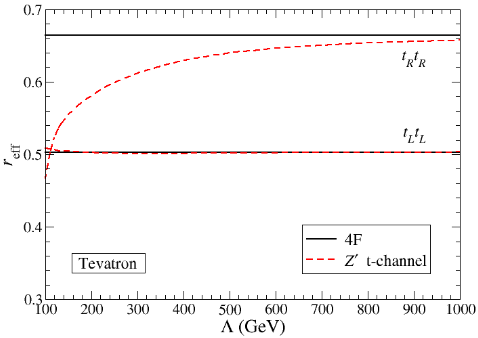
$2.3\times$ tail above 1 TeV

testable soon?

Efficiency at $t\bar{t}$ tail



Efficiency for *tt* at Tevatron



Efficiency for tt at LHC