Review of Top Quark Physics: Theory

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Université catholique de Louvain, Belgium
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#tops@LHC: 276.830
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#tops@LHC: 2 7 6 . 8 7 0
OUTLINE
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• The importance of being Top
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- The importance of being Top
- Precision SM Top Physics
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- Top as tool for BSM pheno: strategies with examples
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• Outlook
Top is special

In the SM, it is the ONLY quark
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In the SM, it is the **ONLY** quark

1. with a “natural mass”

\[ m_{\text{top}} = y_t \frac{v}{\sqrt{2}} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1 \]

It “strongly” interacts with the Higgs sector.
Top is special

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\[ m_{\text{top}} = y_t v / \sqrt{2} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1 \]

It “strongly” interacts with the Higgs sector.

It can easily excite the Higgs
Top is special

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It “strongly” interacts with the Higgs sector.

2. that decays semi-weakly, and before hadronizing

\[ \tau_{\text{had}} \approx \frac{h}{\Lambda_{\text{QCD}}} \approx 2 \cdot 10^{-24} \text{ s} \]
\[ \tau_{\text{top}} \approx \frac{h}{\Gamma_{\text{top}}} = \frac{1}{(G_F m_t^3 |V_{tb}|^2 8\pi \sqrt{2})} \approx 5 \cdot 10^{-25} \text{ s} \]
(with \( h = 6.6 \cdot 10^{-25} \text{ GeV s} \))

Compare with \( \tau_b \approx \frac{(G_F^2 m_b^5 |V_{bc}|^2 k)^{-1}}{10^{-12} \text{ s}} \)

It is a “naked” quark : flavor and EW physics at their best!
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**Top is special**

Largest cross section (LO at $\alpha_s^2$):

- $\sim 10 \text{ pb at Tevatron}$
- $\sim 150 \text{ pb at LHC7}$

Precision physics studies
Strong

Largest cross section (LO at $\alpha s^2$):

~ 10 pb at Tevatron
~ 150 pb at LHC7

Precision physics studies

Weak

Weak process: same diagrams as the top decay!

Cross sections smaller than QCD but enhanced by a lower energy cost:

~ 3 pb at Tevatron
~ 60 pb at LHC7

Three independent channels.
We know a lot already from the Tevatron...
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- Top quark mass: 173.3 ± 1.1 GeV
- ttbar cross section
- W-boson helicity fractions
- Spin correlations between the top quarks are measured by fitting a double distribution
- Forward-backward asymmetry: $A_{FB} = 0.15 \pm 0.07 \pm 0.02$
- $m_{tt}$, $p_t$, $H_T$ distributions
- Decay width: $\Gamma_t < 7.4$ GeV at 95% C.L.
- Branching fraction: 
  $(t\rightarrow W^+b)/(t\rightarrow W^+q) > 0.61$ at 95% C.L.
- Electric charge: $Q_t = -4/3$ excluded at 87% C.L
- Single top production cross section
- Measurement of $|V_{tb}| = 0.88 \pm 0.07$
- Discrimination between t- and s-channel production
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see K. Soustruznik’s talk

see A. Lister’s talk

see K. Rao’s talk
...AND MORE IS COMING FROM THE LHC!
...AND MORE IS COMING FROM THE LHC!
...AND MORE IS COMING FROM THE LHC!

\[ \sigma_{(ttbar)} \]

\[ \sigma \quad \text{pb} \]

- NLO QCD (pp)
- Approx. NNLO (pp)
- NLO QCD (p\bar{p})
- Approx. NNLO (p\bar{p})

\[ \sigma_{(t)} \]

- ATLAS 180 ± 18 pb
- CMS 158 ± 19 pb

\( \sqrt{s} \) / TeV

- CMS Preliminary, 35.9 pb\(^{-1}\)
- D0
- CDF
- NLO 5f
...AND MORE IS COMING FROM THE LHC!

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\[ \frac{\sigma}{pb} \]

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23rd Rencontres de Blois - May/June 2011

Monday 30 May 2011
...AND MORE IS COMING FROM THE LHC!

\[ \sigma_{\text{ttbar}} \]

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**t-channel single top quark production**

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**σ**

- \( \sigma_{\text{ttbar}} \)
- \( \sigma(t) \)

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```
σ_{tt}\quad[pb]
```

```
σ\quad[pb]
```

```
\sqrt{s} / TeV
```

```
A_c\quad=0.018±0.034
```

```
E_T^{miss}\quad[GeV]
```

```
m_{tt}\quad[GeV/c^2]
```

```
N_\geq4, m_{\geq4}\quadat\sqrt{s} = 7\ TeV
```

```
N_{jets}\quaddata\quadQCD\quadZ/\gamma^{*}\rightarrow t\bar{t}\quad(+)\ light\ jets
```

```
Data\quadQCD\quadZ/\gamma^{*}\rightarrow t\bar{t}\quad(+)\ light\ jets\quadW\rightarrow l\nu\quad(+)\ light\ jets\quadSingle-Top
```

```
Events\ per\ 10\ GeV\quadEvents\ / 50\ GeV\cdot c^2
```

```
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...AND MORE IS COMING FROM THE LHC!

see M. Saleem's and M.A. Martin's talks
Can theorists match the wealth and accuracy of experimental results?
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PROGRESS IN SM TOP PREDICTIONS

Top pair cross section and distributions:

• Updates of total top pair cross section (NLO QCD + threshold res. (NLL)) Moch, Uwer; Cacciari et al; Kidonakis, Vogt
• NNLL extensions at threshold: two slightly different definitions of threshold Czakon et al; Beneke et al; Ahrens et al.
• Forward-Backward asymmetry from threshold resummation Almeida et al; Ahrens et al; Antunano et al; Kidonakis
• Top pair invariant mass very close to production threshold (resonance peak) Hagiwara et al; Kiyo et al.
• Partial results towards top pair total rate at NNLO QCD Czakon; Bonciani et al...

Top pair + jets: top as a background to Higgs searches: H \rightarrow W^+W^- and ttH

• pp \rightarrow tt+jet Dittmaier et al.; Melikov, Schulze
• pp \rightarrow tt bb Bredenstein et al.; Bevilacqua et al.
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• tt spin correlations revisited Mahlon, Parke; Bernreuther, Si

Single-top:

• Single top t-channel production at NLO QCD in 5 and 4 flavor schemes Campbell, Frederix, FM, Tramontano
• Single top including decay at NLO QCD Falgari et al.

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EXAMPLE 1: SIGMA(T TBAR)

\[
\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \rightarrow X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})
\]
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Total cross section at NLO:

\[ \sigma^1 = \# \frac{\beta}{\beta} + \# \log^2 \beta + \# \log \beta + c_1 \]

[Dawson et al, Beenakker et al, Bonciani et al, Kao, Wackeroth, Bernreuther et al, Kuhn, Scharf, Uwer]

\[ \beta = \sqrt{1 - \frac{4m_t^2}{s}} \]
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Total cross section at NNLO: [Czakon et al. , Moch et al., Beneke et al.Ahrens et al., Kornert et al.]

\[ \sigma^2 = \frac{\#}{\beta^2} + \frac{\# \log^2 \beta + \# \log \beta + \#}{\beta} + \# \log^4 \beta + \# \log^3 \beta + \ldots + c_2 \]
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\sigma^2 = \frac{\#}{\beta^2} + \frac{\# \log^2 \beta + \# \log \beta + \#}{\beta} + \# \log^4 \beta + \# \log^3 \beta + \ldots + c_2
\]

Beware: NNLO corrections not known exactly yet!!
PROGRESS IN SM TOP PREDICTIONS:
EXAMPLE 1: SIGMA(T TBAR)
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Approximated NNLO results:
very good scale dependence improvement:
**PROGRESS IN SM TOP PREDICTIONS:**

**EXAMPLE 1: SIGMA(T TBAR)**

Approximated NNLO results: very good scale dependence improvement:

Even better if the MSbar mass is used as a parameter in the calculation: possibility of extracting the mass from the cross section.
PROGRESS IN SM TOP PREDICTIONS: EXAMPLE 1: SIGMA(T T BAR)

Approximated NNLO results:
very good scale dependence improvement:

Different approach (SCET).
Prediction is somewhat lower than previous results.
Differences are smaller at the LHC.
PROGRESS IN SM TOP PREDICTIONS: EXAMPLE 2: WWBB

• Calculations beyond LO so far used the narrow width approximation for the top quark pair production: tops are assumed to be stable
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• In fact, there are quite a few more diagrams of the same order...
**PROGRESS IN SM TOP PREDICTIONS: EXAMPLE 2: WWBB**

- Calculations beyond LO so far used the narrow width approximation for the top quark pair production: tops are assumed to be stable.

- However, top quarks decay, so the true LO diagram is this one.

- In fact, there are quite a few more diagrams of the same order...

- Gauge invariance guides us to include also single-resonant and non-resonant production. Note that there is interference between the diagrams above.
Recently, the full NLO computations to the WWbb process were calculated by two independent groups \textit{Denner et al.; Bevilacqua et al.}.

Consistent description of top pair, single top and non-resonant contributions at NLO

Particularly important when cuts require tops to be off-shell

No need to disentangle top pair and Wt and apply separate K-factors when studying the “top” background to e.g. $H \rightarrow WW$
Recently, the full NLO computations to the WWbb process were calculated by two independent groups Denner et al.; Bevilacqua et al.

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Figure 2: Representative Feynman diagrams contributing to the virtual corrections to the partonic subprocess $gg \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at $O(\alpha_3s\alpha_4)$. As explained before, the process under consideration requires a special treatment of unstable top quarks, which is achieved within the complex-mass scheme [40]. At the one-loop level the appearance of a non-zero top-quark width in the propagator requires the evaluation of scalar integrals with complex masses, for which the program...
PROGRESS IN SM TOP PREDICTIONS: 
EXAMPLE 2: WWBB

• Compared to the LO WWbb production, the NLO corrections do not lead to an overall change in normalization:

![Graph showing differential cross section distributions as a function of the missing transverse momentum and the transverse momentum of the charged leptons.](image)
**PROGRESS IN SM TOP PREDICTIONS: EXAMPLE 3: COLOR CHARGE ASYMM.**

\[ A_{CC}^{t\bar{t}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)} \]

Other definitions are used: lab frame at Tevatron, central charge [Antunano, et al.] and one-side asymmetries [Wang et al. 2010] at the LHC which depend on a cut. Acc at the LHC has been introduced by CMS (in terms of pseudo-rapidity). LHCB does not need any special definition [Kagan et al.]
PROGRESS IN SM TOP PREDICTIONS: EXAMPLE 3: COLOR CHARGE ASYMM.

Intuitive picture:

\[ A_{soft} = A_{born} \]

In the soft limit

\[ |A_{soft}|^2 \simeq |A_{born}|^2 \left( \frac{q \cdot t}{q \cdot k t \cdot k} + \frac{\bar{q} \cdot \bar{t}}{\bar{q} \cdot k \bar{t} \cdot k} \right) \]

\[ q \cdot t = E_q E_t (1 - \cos \theta) \]

The probability to emit a gluon is larger the more the top is accelerated (like in QED) and therefore going backwards, so the contribution to the \( A_{FB} \) asymmetry is negative

\[ P(\text{downwards}) < P(\text{upwards}) \]

The virtuals have to cancel the soft divergences of the reals and therefore the contribution is of the opposite sign and in fact positive and much larger.
**PROGRESS IN SM TOP PREDICTIONS: EXAMPLE 3: COLOR CHARGE ASYMM.**

<table>
<thead>
<tr>
<th>$M_{t\bar{t}} &lt; 450$ GeV</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>CDF</strong></td>
<td><strong>MCFM</strong></td>
</tr>
<tr>
<td>$-0.116 \pm 0.154$</td>
<td>$0.475 \pm 0.114$</td>
</tr>
<tr>
<td>$0.040 \pm 0.006$</td>
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de facto
confirmed by D0
and by dilepton channel in CDF.
PROGRESS IN SM TOP PREDICTIONS:
EXAMPLE 3: $A_{FB}$ (COLOR CHARGE ASYMM.)

$$A_{t\bar{t}CC} = \frac{A\alpha_S^3 + B\alpha_S^4 + \ldots}{C\alpha_S^2 + D\alpha_S^3 + \ldots}$$

Observable only known only at the leading order!
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$\alpha^4_S$ (NNLO) calculation for the sigma(ttbar) not available yet. However,

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   [Almeida et al; 2010 Ahrens et al. 2010; Antunano et al 2010.; Kidonakis 2011]

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Note, on the other hand, the interesting pattern:

$tt\bar{t}$ : LO=0 + Virtual>0 (large) + Real<0 (small) = 0.05
$t t\bar{t} j$ : LO<0 (-0.08) + Virtual>0 (large) + Real<0 (small) = -0.02
$t t\bar{t} jj$ : LO <0

Virtuals always dominate : what about the two-loop contributions? to be seen...
OUTLINE

- The importance of being Top
- Precision SM Top Physics
- Top as tool for BSM pheno: strategies with examples*
- Outlook

*see also G. Moreau’s talk
Ok, top is special and a lot of data coming, but why are we getting so excited about it?
Ok, top is special and a lot of data coming, but why are we getting so excited about it?
Top as a link to BSM

The top quark dramatically affects the stability of the Higgs mass. Consider the SM as an effective field theory valid up to scale $\Lambda$:

\[ m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \]

Putting numbers, I have:

\[ (200 \text{ GeV})^2 = m_{H0}^2 + [-(2 \text{ TeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2] \left( \frac{\Lambda}{10 \text{ TeV}} \right)^2 \]
One can actually prove that this case in model independent way, i.e. that the scale associated with top mass generation is very close to that of EWSB.
Top as a link to BSM

There have been many different suggestions! Fortunately, we can say that they group in 1 + 3 large classes:

1. **Denial**: There is no problem. Naturalness is our problem not Nature’s. Pro’s: we’ll find the Higgs. Cons: that’s it.

2. **Weakly coupled model at the TeV scale**: Introduce new particles to cancel SM “divergences”.

3. **Strongly coupled model at the TeV scale**: New strong dynamics enters at \( \sim 1 \text{ TeV} \).

4. **New space-time structure**: Introduce extra space dimensions to lower the Planck scale cutoff to 1 TeV.
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Top parters, new scalars/vectors possibly strongly coupled with top.

Top: t-tbar bound states, colorons. Top is not elementary
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---

**Top as a link to BSM**

Top is the only natural quark

Top partners, new scalars/vectors possibly strongly coupled with top.

Top: $t$-$t\bar{t}$ bound states, colorons. Top is not elementary

KK-excitations
BSM: top-down approach

New Physics

Signatures/Observables
BSM: top-down approach

New Physics

Signatures/Observables
BSM: top-down approach

* New Physics model with top partners (SUSY, UED, LH, 4th Gen..)

* Consider viable benchmark points.

* Identify the signatures with top.

* Set exclusion limits on the model parameters

* Optional: learn “model independent” lessons...
BSM: top-down approach

Examples: signatures with top:

- $\tilde{t}\tilde{t}^* \rightarrow tt + X$, $\tilde{g}g \rightarrow tt (\tilde{t}\tilde{t}) + X$

- $b'b' \rightarrow t\bar{t} W^- W^+$

- $t't' \rightarrow b\bar{b} W^+ W^-$

- $t't' \rightarrow Z Z t\bar{t}$

- 4tops

In general, very rich and energetic final states, large $H_T$, very spectacular and "easy" to detect in principle.
Looks great, if one model at the time is studied.
In fact, very difficult to discriminate which NP leads to it.
Bottom-up approach

New Physics

Signatures/Observables
Bottom-up approach

New Physics

Signatures/Observables
Model independent (bottom-up) strategy for New Physics:

1. Focus on a specific SM observable that is
   a. naturally sensitive to BSM
   b. is well-predicted & possibly “background free”

   and look for deviations

2. Look for “exotic top signatures” (no-SM equivalent),
Bottom-up approach

New Physics

Signatures/Observables
Bottom-up approach

New Physics

Signatures/Observables
Bottom-up approach

New Physics

Standard

Signatures/Observables
Bottom-up approach

New Physics

Standard

Exotic

Signatures/Observables
Bottom-up approach

New Physics

Standard  Exotic

Signatures/Observables
New Physics: Two possibilities
New Physics: Two possibilities

SM

New Physics

\[ \Lambda \]

Energy
New Physics: Two possibilities

SM

New Physics

Energy

23rd Rencontres de Blois - May/June 2011
New Physics: Two possibilities

\[ q \rightarrow Z' \rightarrow f \]

\[ \bar{q} \rightarrow \bar{f} \]

\[ q \rightarrow Z' \rightarrow \bar{q} \]

\[ \bar{q} \rightarrow f \]

New Physics

Energy

\[ \Lambda \]
New Physics: Two possibilities

\[ \Lambda = M \]

New Physics

\[ \frac{1}{p^2 - M^2} \]

Energy
New Physics: Two possibilities

\[ \frac{1}{p^2 - M^2} \]

\[ \frac{g^2}{M^2} \]

\[ \Lambda = M \]

New Physics
New Physics: Two possibilities

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{g^2}{M^2} \bar{\psi}\psi\bar{\psi}\psi \]
New Physics: Two possibilities

\[ \hbar = c = 1 \]
\[ \dim A^\mu = 1 \]
\[ \dim \phi = 1 \]
\[ \dim \psi = 3/2 \]

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\dim=6} \]

Bad News: > 60 operators [Buchmuller, Wyler, 1986]
Good News: a handful are unconstrained and can significantly contribute to top physics!
[Aguilar-Saavedra 2010, Willenbrock et al. 2010, Degrande et al. 2010]
Bottom-up approach

New Physics

Standard

signatures/observables

Exotic
Bottom-up approach

New Physics

Standard

Exotic

signatures/observables
Bottom-up approach

New Physics

- Resonant
- Standard
- Exotic

signatures/observables
Bottom-up approach

New Physics

- Resonant
- Non-resonant

- Standard
- Exotic

signatures/observables
**Bottom-up approach**

New Physics

- Resonant
- Non-resonant

signatures/observables

- Standard
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Monday 30 May 2011
MODEL INDEPENDENT BSM SEARCHES: EXAMPLES

I. Search for resonances in $m_{ttbar}$ (and boosted tops)

II. EFT approach to $ttbar$ (including $A_{FB}$)

III. (Exotic: Same sign tops)
MODEL INDEPENDENT BSM SEARCHES: EXAMPLES

I. Search for resonances in $m_{\text{ttbar}}$ (and boosted tops)

II. EFT approach to ttbar (including $A_{FB}$)

III. (Exotic: Same sign tops)
Interesting observable.

Shape very well predicted.

This could be also used to measure the top mass!

Reconstruction systematics is different from the usual top mass invariant mass reconstruction.

Any BSM effect would distort this shape =>

Model independent search for new Physics!
New Resonances in ttbar

In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.

Given the large number of models, in this case is more efficient to adopt a “model independent” search and try to get as much information as possible on the quantum numbers and coupling of the resonance.
**New Resonances in ttbar**

In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.

Given the large number of models, in this case is more efficient to adopt a “model independent” search and try to get as much information as possible on the quantum numbers and coupling of the resonance.

To access the spin of the intermediate resonance spin correlations should be measured.

It therefore mandatory for such cases to have MC samples where spin correlations are kept and the full matrix element $pp\rightarrow X\rightarrow tt\rightarrow 6f$ is used.
## New Resonances in $t\bar{t}b\bar{b}$

<table>
<thead>
<tr>
<th>Spin</th>
<th>Color</th>
<th>$(1, \gamma_5)$</th>
<th>SM-interf</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>$(1,0)$</td>
<td>no</td>
<td>Scalar</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>$(0,1)$</td>
<td>no</td>
<td>PseudoScalar</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>$(0,1)$</td>
<td>yes</td>
<td>Boso-phobic</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>$(0,1),(1,0)$</td>
<td>no</td>
<td>Techni-$\pi_0[8]$</td>
</tr>
<tr>
<td>0</td>
<td>[sm,sm]</td>
<td>yes/no</td>
<td>yes/ no</td>
<td>$Z'$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$(1,0),(0,1),(1,1),(1,-1)$</td>
<td>yes</td>
<td>vector</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>$(1,0)$</td>
<td>yes</td>
<td>coloron/kk-gluon</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>$(0,1)$</td>
<td>“yes”</td>
<td>axigluon</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>--</td>
<td>yes</td>
<td>kk-graviton</td>
</tr>
</tbody>
</table>

[Frederix, FM, arXiv:0712.2355]
New Resonances in ttbar

1. Discovery

2. Spin

3. Couplings
New Resonances in ttbar

1. Discovery

2. Spin

3. Couplings
New Resonances in ttbar

1. Discovery

2. Spin

3. Couplings
New Resonances in t\bar{t}bar

1. Discovery

2. Spin

3. Couplings
New Resonances in ttBar

1. Discovery

2. Spin

3. Couplings
New Resonances in ttbar

1. Discovery

2. Spin

3. Couplings

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_+ d \cos \theta_-} = \frac{1}{4} \left( 1 + \kappa_+ \kappa_- D \cos \theta_- \cos \theta_+ \right)
\]
New Resonances in $t\bar{t}$bar: Boosted tops

[Kaplan et al., 2008, Thaler et al., 2008, Almeida et al. 2008, Salam 2008]
See Abdesselam, ArXiv:1012.5412 [hep-ph] and Boost2011 Conference in May

“Top quarks : LHC = Bottom quarks : Tevatron”

see M. Takeuchi’s talk
MODEL INDEPENDENT BSM SEARCHES: EXAMPLES

I. Search for resonances in $m_{ttbar}$ (and boosted tops)

II. EFT approach to $t \bar{t}$ production

III. (Exotic: Same sign tops)
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Effective Field Theory Approach to t tbar Production

[Aguilar-Saavedra 2010, Willenbrock et al. 2010, Degrande et al 2010]

### CP-even

<table>
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<td>$O_{qq}^{(1,3)} = (\bar{q} \gamma_\mu \tau^I q^I)(\bar{q} \gamma^\mu \tau^I q)$</td>
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<td>7 four-quark operators</td>
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Very few operators of dim-6:

Dim-6 operators that affect top pair production at tree level by interference with the SM (QCD) amplitudes (we neglect weak corrections)
Effective Field Theory Approach

t to t\overline{t}bar production

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Dim-6 operators that affect top pair production at tree level by interference with the SM
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**Top-philic operators**
(modifying top couplings and not only gluons couplings)

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One can show that you end up with five main operators,

\[ \mathcal{L}_{t\bar{t}} = \mathcal{L}_{t\bar{t}}^{SM} + \frac{1}{\Lambda^2} \left[ g_h \mathcal{O}_{hg} + c_R \mathcal{O}_{Rg} + a_R \mathcal{O}^8_{Ra} + (R \leftrightarrow L) \right] \]

and in case one is interested only in total rates (and spin independent / FB symmetries) only three parameters are left: \( g_h, c_V = c_R + c_L \) and \( a_A = a_R - a_L \)

**Glueon fusion**

Corrections from \( c_{hg} \) only
$\sigma(t \bar{t})$ : Tevatron vs LHC

85% at TeV

VS

80% at LHC7
The gg channel is only very roughly constrained!!! We might have missed some big and important NP effect connected with an gg initial state (such a scalar...). EFT gives us the possibility of studying deviations in a model independent way.
Effective Field Theory Approach to t tbar Production

\[
\frac{d\sigma}{dt} (gg \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} + \sqrt{2}\alpha_s g_s \frac{v m_t}{s^2} \frac{c_{\text{ch}}}{\Lambda^2} \left( \frac{1}{6\tau_1 \tau_2} - \frac{3}{8} \right)
\]

\[
\frac{d\sigma}{dt} (q\bar{q} \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} \left( 1 + \frac{c_{Vv} \pm \frac{c_{Vv}'}{2}}{g_s^2} \frac{s}{\Lambda^2} \right) + \frac{1}{\Lambda^2} \frac{\alpha_s}{9s^2} \left( c_{Aa} \pm \frac{c_{Aa}'}{2} \right) s(\tau_2 - \tau_1) + 4g_s c_{\text{ch}} \sqrt{2} v m_t
\]

\[
\tau_1 = \frac{m_t^2 - t}{s}, \quad \tau_2 = \frac{m_t^2 - u}{s}, \quad \rho = \frac{4m_t^2}{s}, \quad m_t^2 - t = \frac{s}{2} (1 - \beta \cos \theta)
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Effective Field Theory Approach
to $t$ $\bar{t}$ Production

$$\frac{d\sigma}{dt}(gg \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} + \sqrt{2}\alpha_s g_s \frac{v m_t}{s^2} \frac{c_{\text{ch}}}{\Lambda^2} \left( \frac{1}{6\tau_1 \tau_2} - \frac{3}{8} \right)$$

$$\frac{d\sigma}{dt}(q\bar{q} \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} \left( 1 + \frac{c_{Vv} \pm \frac{c'_{Vv}}{2}}{g_s^2} \frac{s}{\Lambda^2} \right) + \frac{1}{\Lambda^2 \cdot 9 s^2} \left( \left(c_Aa \pm \frac{c'_{Aa}}{2} \right) s(\tau_2 - \tau_1) + 4g_s c_{\text{ch}} \sqrt{2} v m_t \right)$$

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1. Extremely simple formulas!!
**Effective Field Theory Approach to $t$ Tbar Production**

\[
\frac{d\sigma}{dt}(gg \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} + \sqrt{2}\alpha_s g_s \frac{vm_t}{s^2} \frac{c_{h\gamma}}{\Lambda^2} \left( \frac{1}{6\tau_1\tau_2} - \frac{3}{8} \right)
\]

\[
\frac{d\sigma}{dt}(q\bar{q} \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} \left( 1 + \frac{c_{V\nu} + c'_{V\nu}}{2g_s^2} \frac{s}{\Lambda^2} \right) + \frac{1}{\Lambda^2} \frac{\alpha_s}{9s^2} \left( c_{A\alpha} + \frac{c'_{A\alpha}}{2} \right) s(\tau_2 - \tau_1) + 4g_s c_{h\gamma} \sqrt{2}vm_t
\]

\[
\tau_1 = \frac{m_t^2 - t}{s}, \quad \tau_2 = \frac{m_t^2 - u}{s}, \quad \rho = \frac{4m_t^2}{s}, \quad m_t^2 - t = \frac{s}{2} (1 - \beta \cos \theta)
\]

1. Extremely simple formulas!!

2. The operator $O_{h\gamma}$ can hardly be distinguished from the SM in gluon fusion
**Effective Field Theory Approach to t tbar Production**

\[
\frac{d\sigma}{dt} (gg \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} + \sqrt{2} \alpha_s g_s \frac{vm_t}{s^2} \frac{c_{hg}}{\Lambda^2} \left( \frac{1}{6\tau_1 \tau_2} - \frac{3}{8} \right)
\]

\[
\frac{d\sigma}{dt} (q\bar{q} \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} \left( 1 + \frac{c_{Vv} + c_{V'v}}{2} \frac{g_s^2 s}{\Lambda^2} \right) + \frac{1}{\Lambda^2} \frac{\alpha_s}{9s^2} \left( c_{Aa} + \frac{c_{A'a}}{2} \right) s(\tau_2 - \tau_1) + 4g_s c_{hg} \sqrt{2vm_t}
\]

\[
\tau_1 = \frac{m_t^2 - t}{s}, \quad \tau_2 = \frac{m_t^2 - u}{s}, \quad \rho = \frac{4m_t^2}{s}, \quad m_t^2 - t = \frac{s}{2} (1 - \beta \cos \theta)
\]

1. Extremely simple formulas!!

2. The operator $O_{hg}$ can hardly be distinguished from the SM in gluon fusion

3. Distortions in the shape of the distributions can only come from qq annihilation ➔ small effects at LHC

4. Even and odd contributions for qq → t\bar{t}, the latter give rise to $A_{FB}$
Effective Field Theory Approach to t ttbar Production

- The pp $\rightarrow$ ttbar total cross section at Tevatron depends on both $c_{hg}$ and $c_{V\nu}$ and constrains thus a combination of these parameters.

![Graph showing the relationship between $c_{V\nu} \times (1 \text{ TeV}/\Lambda)^2$ and $c_{hg} \times (1 \text{ TeV}/\Lambda)^2$]
The pp $\rightarrow$ ttbar total cross section at Tevatron depends on both $c_{hg}$ and $c_{Vv}$ and constrains thus a combination of these parameters.

**Effective Field Theory Approach to ttbar production**

![Graph showing total cross section and tt invariant mass shape](image-url)
The $pp \rightarrow t\bar{t}$ total cross section at LHC strongly depends mostly on $c_{hg}$ and can be directly used to constrain the allowed range for $c_{hg}$.
Effective Field Theory Approach to $t\bar{t}$ production: constraints

**Diagram Description:**
- The diagram illustrates the measured cross-section $\sigma_{t\bar{t}} = \sigma_{SM}$.
- The axes represent $(4$-fermion operator)$^2$ and $(chromomagnetic moment operator)$. 
- The Tevatron and LHC regions are marked with different lines and colors. 
- The LHC points are at 7 TeV and 14 TeV, showing measured values.
- Specific percentage uncertainties are indicated on the diagram (e.g., ±20%, ±10%)

**Equations:**
- $c_V \times (1\text{TeV}/\Lambda)^2$
- $c_{h\gamma} \times (1\text{TeV}/\Lambda)^2$

**Notes:**
- Monday 30 May 2011
Effective Field Theory Approach to $t\bar{t}$ production: $A_{FB}$

$$A_{FB} \equiv \frac{\sigma (\cos \theta_t > 0) - \sigma (\cos \theta_t < 0)}{\sigma (\cos \theta_t > 0) + \sigma (\cos \theta_t < 0)} \text{ lab. frame}$$

$$A_{FB}^{SM} = 0.05 \pm 0.015, \quad A_{FB}^{EXP} = 0.15 \pm 0.05(\text{stat}) \pm 0.024(\text{syst}),$$

$$\delta A_{FB}^{\text{dim}6} = \left( 0.0342^{+0.016}_{-0.009} c_{Aa} + 0.0128^{+0.0064}_{-0.0036} c'_{Aa} \right) \times \left( \frac{1 \text{ TeV}}{\Lambda} \right)^2$$

$c_{Aa}$ and $c'_{Aa}$ are only constrained by the asymmetry and not by the total cross section or the invariant mass distribution.
Effective Field Theory Approach to t tbar production: $A_{FB}$

\[ A_{FB} \equiv \frac{\sigma (\cos \theta_t > 0) - \sigma (\cos \theta_t < 0)}{\sigma (\cos \theta_t > 0) + \sigma (\cos \theta_t < 0)} \quad \text{lab. frame} \]

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\[ \delta A_{FB}^{\text{dim}6} = \left( 0.0342^{+0.016}_{-0.009} c_{Aa} + 0.0128^{+0.0064}_{-0.0036} c'_{Aa} \right) \times \left( \frac{1 \text{ TeV}}{\Lambda} \right)^2 \]

$C_{Aa}$ and $C'_{Aa}$ are only constrained by the asymmetry and not by the total cross section or the invariant mass distribution.

Link to resonant models possible!
Example: axigluon

\[ c_{Aa}/\Lambda^2 = -2g^q_A g^t_A/m_A^2 \]
Effective Field Theory Approach to t tbar production: Summary

Non-resonant top philic new physics can be probed using measurements in top pair production at hadron colliders.

This model-independent analysis can be performed in terms of 8 operators.

Observables depend on different combinations of only 4 parameters:

\[
\begin{align*}
\sigma(gg \rightarrow t\bar{t}), \frac{d\sigma(gg \rightarrow t\bar{t})}{dt} & \leftrightarrow c_{hg} \\
\sigma(q\bar{q} \rightarrow t\bar{t}) & \leftrightarrow c_{hg}, c_{VV}
\end{align*}
\]

\[
\begin{align*}
\frac{d\sigma(q\bar{q} \rightarrow t\bar{t})}{dm_{t\bar{t}}} & \leftrightarrow c_{hg}, c_{VV} \\
A_{FB} & \leftrightarrow c_{Aa} \\
\text{spin correlations} & \leftrightarrow c_{hg}, c_{VV}, c_{Av}
\end{align*}
\]
MODEL INDEPENDENT BSM SEARCHES: EXAMPLES

I. Search for resonances in $m_{tt\bar{t}}$ (and boosted tops)

II. EFT approach to $t\bar{t}$ production

III. Exotic: same sign tops
MODEL INDEPENDENT BSM SEARCHES: EXAMPLES

I. Search for resonances in $m_{tt\bar{t}}$ (and boosted tops)

II. EFT approach to t tbar production

III. Exotic: same sign tops
SAME SIGN TOPS

[Rajamaran et al., 2011][C. Degrande et al., 2011], [Aguilar-Saavedra et al. 2011], [E. Berger et al., 2011], [J. Cao et al., 2011] [Hao Zhang et al., 2010], [C. Bauer et al. 2010], [S. Jung et al. 2009] [J. Gao et al. 2009], [S. Bar-Shalom et al., 2008]....

Exotic signature: “easy” to identify in the same sign channel (double lepton decay) or in the charge asymmetry (single lepton decay). At the LHC enhanced by PDF.
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[Rajamaran et al., 2011][C. Degrande et al., 2011], [Aguilar-Saavedra et al. 2011], [E. Berger et al., 2011],[J. Cao et al., 2011] [Hao Zhang et al., 2010],[C. Bauer et al. 2010], [S. Jung et al. 2009] [J. Gao et al. 2009],[S. Bar-Shalom et al ,2008]....

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s-channel
3bar or 6 color

s-channel
1 or 8 color
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Exotic signature: “easy” to identify in the same sign channel (double lepton decay) or in the charge asymmetry. (single lepton decay). At the LHC enhanced by PDF.

The t-channel can be linked to the $A_{FB}$ for neutral particle exchanges!

s-channel
3bar or 6 color

t-channel
1 or 8 color
**SAME SIGN TOPS**

Resonant approach:

List all possible particles that can be exchanged either in the s-channel or in the t-channel

\[ \begin{align*}
\mathcal{B}_\mu & \quad (1, 1)_0 & - \left( g_{ij}^q \bar{q}_L i \gamma^\mu q_{Lj} + g_{ij}^u \bar{u}_R i \gamma^\mu u_{Rj} + g_{ij}^d \bar{d}_R i \gamma^\mu d_{Rj} \right) \mathcal{B}_\mu & \quad g = g^T \\
\mathcal{W}_\mu & \quad (1, \text{Adj})_0 & - g_{ij} \bar{q}_L i \gamma^\mu \tau^I q_{Lj} \mathcal{W}_\mu & \quad g = g^T \\
\mathcal{G}_\mu & \quad (\text{Adj}, 1)_0 & - \left( g_{ij}^q \bar{q}_L i \gamma^\mu \frac{\lambda_a}{2} q_{Lj} + g_{ij}^u \bar{u}_R i \gamma^\mu \frac{\lambda_a}{2} u_{Rj} + g_{ij}^d \bar{d}_R i \gamma^\mu \frac{\lambda_a}{2} d_{Rj} \right) \mathcal{G}_\mu & \quad g = g^T \\
\mathcal{H}_\mu & \quad (\text{Adj}, \text{Adj})_0 & - g_{ij} \bar{q}_L i \gamma^\mu \tau^I \frac{\lambda_a}{2} q_{Lj} \mathcal{H}_\mu & \quad g = g^T \\
\mathcal{Q}_\mu^5 & \quad (3, 2)_{-\frac{\lambda}{6}} & - g_{ij} \epsilon_{abc} \bar{u}_{Rib} i \gamma^\mu \epsilon q_{Ljc}^L \mathcal{Q}_\mu^{5a} & \quad \text{h.c.} \\
\mathcal{Y}_\mu^5 & \quad (6, 2)_{-\frac{\lambda}{6}} & - g_{ij} \frac{1}{2} \left[ \bar{u}_{Ria} i \gamma^\mu \epsilon q_{Ljb}^c + \bar{u}_{Rib} i \gamma^\mu \epsilon q_{Lja}^c \right] \mathcal{Y}_\mu^{5ab} & \quad \text{h.c.} \\
\phi & \quad (1, 2)_{-\frac{1}{2}} & - g_{ij}^u \bar{q}_L i u_{Rj} \phi - g_{ij}^d \bar{d}_R i d_{Rj} \tilde{\phi} & \quad \text{h.c.} \\
\Phi & \quad (\text{Adj}, 2)_{-\frac{1}{2}} & - g_{ij}^u \bar{q}_L i u_{Rj} \Phi^a - g_{ij}^d \bar{d}_R i d_{Rj} \tilde{\phi}^a & \quad \text{h.c.} \\
\Omega^4 & \quad (6, 1)_{-\frac{4}{3}} & - g_{ij} \frac{1}{2} \left[ \bar{u}_{Ria} u_{Rjb}^c + \bar{u}_{Rib} u_{Rja}^c \right] \Omega^{ab} & \quad g = g^T \\
\Sigma & \quad (6, \text{Adj})_{-\frac{4}{3}} & - g_{ij} \frac{1}{2} \left[ \bar{q}_{Lia} \tau^I \epsilon q_{Ljb}^c + \bar{q}_{Lia} \tau^I \epsilon q_{Lja}^c \right] \Sigma^{ab} & \quad g = g^T
\end{align*} \]

[Aguilar-Saavedra et al. 2011]
SAME SIGN TOPS

Effective approach:

\[ \mathcal{L}_{qq\rightarrow tt}^{\text{dim}=6} = \frac{1}{\Lambda^2} \left( c_{RR} \mathcal{O}_{RR} + c_{LL}^{(1)} \mathcal{O}_{LL}^{(1)} + c_{LL}^{(3)} \mathcal{O}_{LL}^{(3)} + c_{LR}^{(1)} \mathcal{O}_{LR}^{(1)} + c_{LR}^{(8)} \mathcal{O}_{LR}^{(8)} \right) + h.c. \]

with:

\[ \mathcal{O}_{RR} = [\bar{t}_R \gamma^\mu u_R] [\bar{t}_R \gamma^\mu u_R] \quad \mathcal{O}_{LL}^{(1)} = [\bar{Q}_L \gamma^\mu q_L] [\bar{Q}_L \gamma^\mu q_L] \quad \mathcal{O}_{LL}^{(3)} = [\bar{Q}_L \gamma^\mu \sigma^a q_L] [\bar{Q}_L \gamma^\mu \sigma^a q_L] \]

\[ \mathcal{O}_{LR}^{(1)} = [\bar{Q}_L \gamma^\mu q_L] [\bar{t}_R \gamma^\mu u_R] \quad \mathcal{O}_{LR}^{(8)} = [\bar{Q}_L \gamma^\mu T^A q_L] [\bar{t}_R \gamma^\mu T^A u_R] \]

All the effects given by the (heavy) resonances written before can be written in terms of the operators.
SAME SIGN TOPS

Effective approach:

\[
\mathcal{L}_{\text{dim}=6}^{qq\to tt} = \frac{1}{\Lambda^2} \left( c_{RR} \mathcal{O}_{RR} + c_{LL}^{(1)} \mathcal{O}_{LL}^{(1)} + c_{LL}^{(3)} \mathcal{O}_{LL}^{(3)} + c_{LR}^{(1)} \mathcal{O}_{LR}^{(1)} + c_{LR}^{(8)} \mathcal{O}_{LR}^{(8)} \right) + h.c.
\]

with:

\[
\begin{align*}
\mathcal{O}_{RR} &= [t_R \gamma^\mu u_R] [\bar{t}_R \gamma_\mu u_R] \\
\mathcal{O}_{LL}^{(1)} &= [\bar{Q}_L \gamma^\mu q_L] [\bar{Q}_L \gamma_\mu q_L] \\
\mathcal{O}_{LL}^{(3)} &= [\bar{Q}_L \gamma^\mu \sigma^a q_L] [\bar{Q}_L \gamma_\mu \sigma^a q_L] \\
\mathcal{O}_{LR}^{(1)} &= [\bar{Q}_L \gamma^\mu q_L] [t_R \gamma_\mu u_R] \\
\mathcal{O}_{LR}^{(8)} &= [\bar{Q}_L \gamma^\mu T^A q_L] [\bar{t}_R \gamma_\mu T^A u_R]
\end{align*}
\]

All the effects given by the (heavy) resonances written before can be written in terms of the operators.

\[
\frac{d\sigma}{dt} = \frac{1}{\Lambda^4} \left[ \left( |c_{RR}|^2 + |c_{LL}|^2 \right) \frac{(s - 2m_t^2)}{3\pi s} 
+ \left( |c_{LR}^{(1)}|^2 + \frac{2}{9} |c_{LR}^{(8)}|^2 \right) \frac{(m_t^2 - t)^2 + (m_t^2 - u)^2}{16\pi s^2} 
- \left( |c_{LR}^{(1)}|^2 + \frac{8}{3} \Re \left( c_{LR}^{(1)} c_{LR}^{(8)*} \right) - \frac{2}{9} |c_{LR}^{(8)}|^2 \right) \frac{m_t^2}{24\pi s} \right].
\]

A very simple calculation leads to the differential cross section:
SAME SIGN TOPS

The Tevatron constraints on same-sign tops [CDF/PHYS/EXO/PUBLIC/10466] (pretty weak)

constraints from ttbar cross sections and invariant mass distributions and relations with the $A_{FB}$ (assuming neutral t-channel physics)

Upshot: t-channel scenarios are disfavoured. No constraints for $t\bar{t}$ at the LHC.
OUTLOOK
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- Top-quark physics is still crazy after all these years.
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Enjoy this exciting 2011!
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