Search for Higgs-like particle produced in association with $b$ quarks and measurement of $Z \rightarrow b\bar{b}$ cross section at CDF II

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What if we missed something at low mass?

Di-jet searches at the LHC are pushing the limits for New Physics to really high masses. At low mass (100-300 GeV/c\(^2\)) they are limited by the possibility to trigger low energy \(b\)-jets

CDF II data can help to fill this gap

Outline

- The \(b\)-jet enriched data sample
- Inclusive \(Z \to b\bar{b}\) measurement
- Inclusive \(H \to b\bar{b}\) limit
- \(b\phi \to b\bar{b}b\) limit, \(\phi\) Higgs-like particle
**b-jet enriched data sample**

Overwhelming background from QCD multijet production

Smart on-line selection is a key point for these searches

**Triggering on b-jets**

- Two jets with low energy thresholds (15 GeV/c²)
- Fast $O(10 \mu s)$ and efficient (40%) on-line b-tagging on one jet

  - 5% efficiency for $Z \rightarrow b\bar{b}$
  - 10% efficiency for $H \rightarrow b\bar{b}$

- 5.4 fb$^{-1}$ of integrated luminosity

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**b-jet identification at CDF**

- Displaced vertex
- $L_{xy}$ cut
- Vertex mass separation

Performance:
40% efficiency on $b$-jets
1% fake rate (light jets)
Measurement of inclusive $Z \rightarrow b\bar{b}$ cross section

$Z \rightarrow b\bar{b}$ signal hidden among the overwhelming backgrounds:

- Irreducible QCD $b$-jets pairs
- $c$ and light quarks initiated jets tagged as $b$-jet

Challenging search, but from high pain, high gain!

The $Z \rightarrow b\bar{b}$ as a standard candle to ..

- Determine the Jet Energy Scale ($E_{\text{data}}/E_{\text{MC}}$) for $b$-jets
- Confirm the correctness of all the tools
- Validate the background modeling for the other searches
Measurement of inclusive $Z \rightarrow b\bar{b}$ cross section

Analysis strategy

- Signal searched in a sample with two $b$-tagged jets
- Fit to the invariant mass of the two leading jets using:
  - QCD multijet background templates from data driven technique
  - $Z \rightarrow b\bar{b}$ signal template from Monte Carlo simulation

Background templates

1. Sample with a single $b$-tagged jet and another untagged jet (Bx)
2. Non-$b$ component removed from the single $b$-tagged sample with a cut on the Secondary Vertex mass
3. $b$-tagging parametrizations from simulations for the different jet flavors
4. $b$-tagging parametrizations to simulate the bias on the untagged jet

Templates for Bb, Bc and Bq backgrounds
Measurement of inclusive $Z \to b\bar{b}$ cross section

Fit to the double $b$-tagged sample

CDF II Preliminary 5.4 fb$^{-1}$

Binned maximum likelihood fit

CDF II Preliminary 5.4 fb$^{-1}$

Component Fitted yield in events

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to bb$</td>
<td>$(16.5 \pm 1.2) \times 10^3$</td>
</tr>
<tr>
<td>$Bb+Cb$</td>
<td>$(68.1 \pm 1.1) \times 10^4$</td>
</tr>
<tr>
<td>$bB+bC$</td>
<td>$(19.4 \pm 1.3) \times 10^4$</td>
</tr>
<tr>
<td>$Bq$</td>
<td>$&lt; 175 (1\sigma)$</td>
</tr>
<tr>
<td>$qB$</td>
<td>$&lt; 61 (1\sigma)$</td>
</tr>
</tbody>
</table>

No light quark initiated jets in the double $b$-tagged sample

More than $5\sigma$ significance including systematics

Measurement:

$$\sigma(p\bar{p} \to Z)B(Z \to b\bar{b}) = 1.11 \pm 0.08(\text{stat}) \pm 0.13(\text{sys}) \text{ nb}$$

Theoretical NLO prediction:

$$\sigma(p\bar{p} \to Z)B(Z \to b\bar{b}) = 1.13 \pm 0.02 \text{ nb}$$

Residual $b$-Jet Energy Scale:

$$\text{JES} = 0.993 \pm 0.022 \pm 0.015$$

Data-background

CDF II Preliminary 5.4 fb$^{-1}$

CDF data - multijet bkg

Z$\to$bb PYTHIA 6.2
Limit on the inclusive Standard Model $H \rightarrow b\bar{b}$

Testing a different production mechanism with respect to the one that led to the Tevatron $H \rightarrow b\bar{b}$ evidence

Search validated by the $Z \rightarrow b\bar{b}$ measurement:

- Same event selection
- Same background modeling

Very low $S/\sqrt{B} \sim 0.04$

Upper limit set using CL$_S$ method

Test statistic: $\chi^2$ difference between fits in the B or S+B hypothesis

Result

Observed (expected) limit at 95% C.L. 33 (46) times the Standard Model cross section
Search for $\phi b \rightarrow b\bar{b}b$ process

Signal signature

Narrow neutral scalar $\phi$ into a $b$ quark pair
Additional third $b$ quark to reduce the background

- Bump in $m_{b\bar{b}}$, taken as 2 leading jets invariant mass

Motivation

This search can be included in various theoretical models:

- MSSM Higgs sector
- Dark-matter models with mediator particles with a large coupling to $b$ quarks

The analysis is left in a general context of exotic resonance searches

Tevatron previous combined result (2012)

$2\sigma$ excess
Search for $\phi b \rightarrow b\bar{b}b$ process

Analysis strategy

- Signal searched in a sample with three $b$-tagged jets
- Signal and background modeling based on 2D templates: $x_{\text{tag}}$ vs invariant mass $m_{12}$
- $x_{\text{tag}}$ variable sensitive to the flavor of the jet, carries the information of the SV mass

Background templates

- Starting point: double $b$-tagged sample
- $b$-tagging parametrizations applied to the third untagged jet

![Graphs showing background templates](image-url)
Search for $\phi b \rightarrow b \bar{b} b$ process

2D-fit to triple $b$-tagged data sample

Best fit w/o signal (projection in $m_{12}$)

Best fit with signal (projection in $m_{12}$)

Fit and background templates validated in a control sample

Upper limit set using CL$_S$ method

Test statistic: $\chi^2$ difference between fits in the B or S+B hypothesis

Systematics uncertainties included as nuisance parameters
Summary and conclusion

- Measurement of the $Z \to b\bar{b}$ cross section
  - More than $5\sigma$ significance
  - Validate the search for resonances in $b$-jets final states
  - Measurement of the $b$-Jet Energy Scale

- Limit on the inclusive Standard Model $H \to b\bar{b}$
  - First limit on the inclusive $H \to b\bar{b}$ process

- Limit on the $\phi b \to b\bar{b}b$ process
  - Best limit on the $\sigma \times B$ in the low mass range
  - No excess in the “hot” region $100 - 150$ GeV/$c^2$ found

Tevatron datasets can still give important input to Physics, especially in region of the phase-space not well covered by LHC experiments.
Backup
$b$-tagging data/MC scale factors

CDF II Preliminary 5.4 fb$^1$

CDF data

$\frac{f(E_T)}{E_T} = 0.678$  

$\frac{f(E_T)}{E_T} = 0.823 - 0.003 E_T$

CDF II Preliminary 5.4 fb$^1$

CDF data

$\frac{f(E_T)}{E_T} = 0.863$  

$\frac{f(E_T)}{E_T} = 0.897 - 0.001 E_T$
$Z \rightarrow b\bar{b}$ systematic uncertainties

CDF II Preliminary 5.4 fb$^{-1}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty</th>
<th>$b$-Jet Energy Scale</th>
<th>$Z \rightarrow b\bar{b}$ cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td>5.9%</td>
</tr>
<tr>
<td>Background template statistics</td>
<td>0.004</td>
<td>2.3%</td>
<td></td>
</tr>
<tr>
<td>$c$-quark component in $b\bar{b}$ templates</td>
<td>0.005</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Signal Monte Carlo statistics</td>
<td>0.002</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>$b$-tag energy dependence</td>
<td>0.004</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>$b$-tag scale factor</td>
<td></td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>Trigger and $b$-tag combined scale factor</td>
<td></td>
<td></td>
<td>4%</td>
</tr>
<tr>
<td>Jet Energy Correction</td>
<td></td>
<td>1.4%</td>
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<tr>
<td>Final State Radiation</td>
<td></td>
<td>2.6%</td>
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<tr>
<td>Parton Distribution Functions</td>
<td></td>
<td>1.1%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.008</td>
<td>11.4%</td>
<td></td>
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</tbody>
</table>
\( \phi b \to b\bar{b}b \) control sample

Fit to the triple tagged sample, with one of the jet negative tagged (mistag)

CDF II Preliminary 5.4 fb\(^{-1} \)
\( \phi b \rightarrow \bar{b}b \bar{b} \) systematic uncertainties

CDF II Preliminary 5.4 fb\(^{-1}\)

Systematic uncertainties on the \( \phi b \rightarrow \bar{b}b \bar{b} \) search

<table>
<thead>
<tr>
<th>Source</th>
<th>Variation</th>
<th>Applies to</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>5.9%</td>
<td>signal</td>
<td>rate</td>
</tr>
<tr>
<td>Offline b-tag</td>
<td>5% per jet</td>
<td>signal</td>
<td>rate</td>
</tr>
<tr>
<td>Online and offline b-tag combined</td>
<td>4%</td>
<td>signal</td>
<td>rate</td>
</tr>
<tr>
<td>JES</td>
<td>7 – 4%</td>
<td>signal</td>
<td>rate/shape</td>
</tr>
<tr>
<td>( x_{\text{tag}} )</td>
<td>3%</td>
<td>signal</td>
<td>shape</td>
</tr>
<tr>
<td>PDFs</td>
<td>2%</td>
<td>signal</td>
<td>rate</td>
</tr>
<tr>
<td>Template stat. uncertainty</td>
<td>-</td>
<td>background</td>
<td>shape</td>
</tr>
<tr>
<td>Heavy flavor normalization</td>
<td>5%</td>
<td>background</td>
<td>rate</td>
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