Searching for CHAMPs at CDF

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What are CHAMPs?

CHAMPs are CHArged Massive Particles, stable enough to traverse the detector.

Standard Model extensions predict new massive particles

Most new particle searches assume particles decay promptly

Particles can be long-lived if they have:

- weak coupling constants
- limited phase space
- a conserved quantity
Examples of CHAMPs

- Long-lived 4th generation quarks

- Supersymmetry:
  - stable stop squark
  - NLSP stau in gauge-mediated SUSY breaking
  - Light strange-beauty squarks

- Universal Extra Dimensions (UXDs)
  - Kaluza-Kline modes of SM particles
Universal Extra Dimension Champs

Extra dimensions accessible to all Standard Model fields => Universal

- Must be compactified
- Well motivated, i.e.
  - Could solve hierarchy problem
  - Could require 3 generations
  - Could explain proton stability
  - Provides mechanisms for electroweak and super symmetry breaking

- Momentum conserved in UXD
  - Particles must be pair produced
    - No tree-level contributions to Standard Model observables
    - Would evade limits based upon tree-level contributions of heavy Kaluza-Klein (KK) towers

- Particles possibly stable or long-lived (CHAMPs!)
  - Momentum conservation

- First-level KK quarks nearly degenerate at lowest level
  - But radiative corrections essential for phenomenology
    - LKP could be KK photon
      - Missing Et, not CHAMPs
Limits on CHAMPs

- **Ocean searches**
  - Stable CHAMPs produced by cosmic rays could accumulate in ocean water
    - $M > 230$ GeV (M. Byrne, C. Kolda, P. Regan, PRD 66, 075007 (2002))

- **Direct searches**
  - Run 1 CDF search used $dE/dx$ in the tracker
    - $M > 200$ GeV (strongly produced) (D. Acosta et al. PRL 90, 131801 (2003))
CHAMP Signatures

- CHAMPs have a lot of momentum (they are heavy)
- CHAMPs are hard to stop (they are heavy)
  - Very penetrating
- CHAMPs are slow (they are heavy)
  - Large $dE/dx$
  - Long time-of-flight
- Look for “slow muons”
  - Look for high transverse momentum ($p_T$) tracks in the muon dataset that are slow (long time-of-flight)
Look for CHAMPs in “Muon” Dataset

- Look at events that trigger the muon detectors:
  - Penetrate through the calorimeter to the muon chambers
  - Matching high-$p_T$ track

- Select event with
  - Good high- $p_T$ track
    - $p_T > 40$ GeV/c signal region
    - $20 < p_T < 40$ GeV/c control
  - Good TOF
Use CDF Time-of-Flight to Find Slow Particles

- Interaction region surrounded by tracking (COT), time-of-flight (TOF), calorimetry, and muon detectors
- TOF Timing resolution ~1% on β
- Need candidate time and independent interaction t0
Sources of Background

- **Instrumental effects**
  - Mismeasure event $t_0$
  - Incorrect TOF measurement for CHAMP candidate

- **Cosmic rays**
  - Time of cosmic ray tracks uncorrelated with interaction time, could appear to be CHAMPs
  - Most cosmic rays removed with filter
    - Looks for backward-going track opposite candidate
Evaluate event timing using tight Z’s from bhel0d sample:

- **tight electron**
  - $E_t > 20$ GeV
  - $\text{Had/EM} < 0.055 + 0.00045 \times \text{emTot}$
  - $\text{calIsoRatio} < 0.1$
  - $lshr3 < 0.2$
  - Not a conversion
  - central, fiducial $= 1$
  - $\text{cesStripChi2} < 10$
  - $|\text{cesDeltaZ}| < 3.0$ cm
  - $-3$ cm $< \text{cesQdeltaX} < 1.5$ cm
  - Track $|z0| < 60$ cm
  - at least 5 hits in at least 3 axial and 2 stereo SL
  - Track $P_t > 10$ and ($E/p < 2.0$ or $P_t > 50$)

- **Loose electron:**
  - $E_t > 20$ GeV
  - $\text{Had/EM} < 0.055 + 0.00045 \times \text{emTot}$
  - $\text{calIsoRatio} < 0.1$
  - Not a conversion
  - central, fiducial $= 1$
  - at least 5 hits in at least 3 axial and 2 stereo SL
  - Track $P_t > 10$
  - Track $|z0| < 60$ cm
Z→ee Sample

**Mass**

- **z0**
  - Entries: 11355
  - Mean: 1.047
  - RMS: 24.88
  - \( \chi^2 / \text{ndf} \): 63.59 / 27
  - Constant: 683.6 ± 8.5
  - Mean: 1.299 ± 2.77
  - Sigma: 27.07 ± 0.26

**Pt**

- **Ele Et tight leg**
  - Entries: 11355
  - Mean: 39.30
  - RMS: 8.79

- **looseEleEt**
  - Entries: 11355
  - Mean: 45.31
  - RMS: 16.22

**ele z0 diff**

- **Z0 Difference for Z electrons**
  - Entries: 11355
  - Mean: 0.0008504
  - RMS: 9.205
TOF Measurements

- Compare production time of Z electrons to measure TOF performance
  - 120 ps resolution
    - consistent with TOF production-time error
  - significant non-Gaussian tails

TOF production-time uncertainty
TOF Event $t_0$

- Use non-candidate track TOF production times to measure event $t_0$
- Can measure $t_0$ resolution by splitting tracks from same vertex and comparing

\[
\begin{align*}
\chi^2 / \text{ndf} & = 17.77 / 11 \\
\text{Prob} & = 0.08705 \\
\text{SingleTrkRslt} & = 0.1773 \pm 0.0008
\end{align*}
\]
How well does the TOF work?

- 120 ps resolution for the two legs of $Z \rightarrow ee$
- Hi-side tail is a problem
  - Signal tracks look like CHAMPs if t0 off low or if candidate TOF off high
  - more than 1% above 1 ns even with 7 t0 tracks
  - Need a way to identify TOF mismeasurements!
Track Timing with the COT

- Up to 96 time measurements on a track
- Every hit provides independent time measurement
  - Potentially lots of timing information
  - Large statistics can compensate for low single-hit precision, but overall TOF resolution still better
  - Measure arrival times at wire planes and cell boundaries
    - Can measure track velocity with or without event t0
    - Drift-sign dependent residuals for wrong t0 or \( \beta \).
      » 4.5 ns for \( b=1 \) particle to reach outer SL
      » TOF corrections used in pattern recognition & fit.
  - No non-Gaussian tails!
Time measurements with the COT

- Sense wires
- Field sheet
- Hits
- Track trajectory
Drift direction reverses at wire planes and field sheets. (Also changes at cell boundaries.)
Time measurements with the COT

Systematic shift with drift direction when assumed crossing time is wrong.
Time measurements with the COT

Same track after shifting event $t_0$ by 10 ns
Can estimate production time for all tracks

Assume $\beta = 1$

Calculate average residual for each group of wires with the same drift sign

Take difference in average residual for adjacent groups

Average of these differences yields track $t_{0}$
CDF

COT Track t0

- Compare production times for electrons in $Z \rightarrow e^+e^-$ events

Time resolution = 320 ps Gaussian to at least $3\sigma$

Same plot for TOF
Resolution = 120 ps
Significant non-Gaussian tail
- Use non-candidate track COT t0 to measure event t0
- Can measure t0 resolution by splitting tracks from same vertex and comparing
- Resolution 3x worse than TOF with same # tracks, but more COT tracks
$t_{0COT} - t_{0TOF}$ has 200ps sigma

Mean is not 0: Need to calibrate offset!
Analysis Strategy

- Use track momentum and velocity measurements to calculate mass
- Signal events will have large momentum
  - signal region $p_T > 40$ GeV/c
  - control region $20$ GeV/c $< p_T < 40$ GeV/c
- use control region to predict background shape
Use \( p \) and \( \beta \) to find Mass

\[
m = p \sqrt{\frac{1}{\beta^2} - 1}
\]

- \( \beta > 1 \) unphysical
- Assign negative mass
- Control region and signal region have different momenta, therefore different mass distributions

\( bhel \) Pass W filter
\( p > 40 \)
\( 40 > p > 20 \)
Want to Predict Background Mass Shape

- Assume \( p \) and \( \beta \) are independent
  - Calculate mass bin-by-bin from \( p \) and \( \beta \) histograms
  - Weight by bin contents
  - Gives mass shape prediction

- Works!
  - \( p \) and \( \beta \) are independent in the control sample
Predict signal-region Mass

- Use control-region beta, signal region momentum
- Prediction good
  - not perfect
  - some $p_t - \beta$ correlation
- high-mass tail well modelled

**bhel**
Pass W filter
$p > 40$
prediction
Removing Background

Three sources of high-mass background:

1. mismeasured $t_0$
   - require TOF and COT $t_0$ to agree (within 0.5 ns)

2. mismeasured TOF arrival time
   - require good COT $\chi^2$ when using TOF $\beta$
   - require better COT $\chi^2$ for TOF $\beta$ than $\beta = 1$

3. mismeasured momentum
   - can get high mass for a 6 TeV track with $\beta$ near 1
   - require $\beta$ significantly different from 1
Cleanup Results

W→e ν

(t₀_{COT} - t₀_{TOF}) < 0.5 ns

and $\chi^2_{TOF} < 500$ and $\beta < 0.9$

$(\chi^2_{TOF}/DOF - \chi^2_{\beta=1}/DOF) < -0.2$

and $t₀_{COT} - t₀_{TOF} < 0.5$ ns

and $\beta < 0.9$

These are not yet optimized
W→eν after Cleanup

- W→eν looks fine after cleanup
  - No signal-region events above 120 GeV
  - Prediction matches shape
Champs Data Sample

Champs will be very penetrating

- Even strongly interacting Champs will not scatter significantly
- Will trigger muon detectors!

Use Muon Datasets

- bhmu0d, bhmu0h, bhmu0i
- require CMUP or CMX trigger
  - Slow Champs can be highly ionizing
- do NOT cut on EM, Had energy
- Many Champs pair produced
  - look at 2 highest Pt good muons
  - look at highest Pt good track if only 1 muon
CMUP Control Mass

- Look at Control-Region CMUP Trigger events
  - $\text{Pt} < 40 \text{ GeV/C}$
- Mass shape well predicted
  - $\text{Pt}$ and $\beta$ largely independent
Use Control-Region events to predict background shape in signal region

Expect one event above 120 GeV after cleanup:

\[(t_{0\text{COT}} - t_{0\text{TOF}}) < 0.5 \text{ ns}\]

and \(\chi^2_{\text{TOF}} < 500\)

and \(\beta < 0.9\)
- Use predicted background to find expected 95% CL on signal
- Need Efficiencies to get cross section limit
Look at MC Stop
  - run through same analysis
  - Sharp mass peaks seen
    - Trigger not modeled
  - Still working on efficiencies
    - only want geometric from MC

140 GeV Stop
  646 pb\(^{-1}\)

180 GeV Stop
  8143 pb\(^{-1}\)
CHAMP ID Efficiency

- For ID, Stop must
  - be charged (53%)
  - not rehadronize (43%)
    - only for trigger
  - have track ($\beta > 0.4$)
  - $p_t > 40$ GeV/c (94%-96%)

**120 GeV Stop**
- 2560 pb$^{-1}$

**180 GeV Stop**
- 8143 pb$^{-1}$
CHAMPs Efficiencies

- Measure efficiencies using $W \rightarrow e\nu$
- Net reconstruction efficiency 45%

<table>
<thead>
<tr>
<th></th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vtx ±60cm</td>
<td>95.80%</td>
</tr>
<tr>
<td>W from MaxSumPt</td>
<td>84.5%</td>
</tr>
<tr>
<td>! cosmic</td>
<td>-0.60%</td>
</tr>
<tr>
<td>COT match</td>
<td>84.7%</td>
</tr>
<tr>
<td>TOF Info</td>
<td>81.4%</td>
</tr>
<tr>
<td>delta t0</td>
<td>80.0%</td>
</tr>
<tr>
<td>Net Effic</td>
<td>44.6%</td>
</tr>
</tbody>
</table>
# Expected Stop Signal

<table>
<thead>
<tr>
<th></th>
<th>200 GeV</th>
<th>180 GeV</th>
<th>160 GeV</th>
<th>140 GeV</th>
<th>120 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMUP CMUP</td>
<td>13.58%</td>
<td>11.82%</td>
<td>10.85%</td>
<td>8.79%</td>
<td>7.88%</td>
</tr>
<tr>
<td>CMUP CMX</td>
<td>7.24%</td>
<td>7.47%</td>
<td>6.74%</td>
<td>6.94%</td>
<td>5.47%</td>
</tr>
<tr>
<td>CMUP only fid</td>
<td>24.88%</td>
<td>25.25%</td>
<td>24.71%</td>
<td>23.09%</td>
<td>21.53%</td>
</tr>
<tr>
<td>CMX CMX fid</td>
<td>2.78%</td>
<td>2.31%</td>
<td>1.88%</td>
<td>2.48%</td>
<td>2.27%</td>
</tr>
<tr>
<td>CMX only</td>
<td>11.72%</td>
<td>13.08%</td>
<td>11.35%</td>
<td>12.10%</td>
<td>12.93%</td>
</tr>
<tr>
<td>Total Acc*Trig Effic</td>
<td>60.20%</td>
<td>59.93%</td>
<td>55.53%</td>
<td>53.41%</td>
<td>50.09%</td>
</tr>
<tr>
<td>Pt&gt;40 beta&gt;0.4</td>
<td>95.59%</td>
<td>95.83%</td>
<td>95.24%</td>
<td>95.90%</td>
<td>93.57%</td>
</tr>
<tr>
<td>Net Reconstructed</td>
<td>5.84%</td>
<td>5.82%</td>
<td>5.36%</td>
<td>5.19%</td>
<td>4.75%</td>
</tr>
<tr>
<td><strong>N Expected:</strong></td>
<td><strong>12</strong></td>
<td><strong>22</strong></td>
<td><strong>39</strong></td>
<td><strong>83</strong></td>
<td><strong>171</strong></td>
</tr>
</tbody>
</table>

**NOTE:** Only trigger efficiencies right for 2-CHAMP events.
## Expected Stop Signal

<table>
<thead>
<tr>
<th>MC:</th>
<th>200 GeV</th>
<th>180 GeV</th>
<th>160 GeV</th>
<th>140 GeV</th>
<th>120 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMUP CMUP</td>
<td>2.59%</td>
<td>2.25%</td>
<td>2.07%</td>
<td>1.67%</td>
<td>1.50%</td>
</tr>
<tr>
<td>CMUP CMX</td>
<td>1.36%</td>
<td>1.42%</td>
<td>1.25%</td>
<td>1.27%</td>
<td>1.02%</td>
</tr>
<tr>
<td>CMUP + Track</td>
<td>2.15%</td>
<td>2.13%</td>
<td>2.13%</td>
<td>2.02%</td>
<td>1.70%</td>
</tr>
<tr>
<td>CMUP only fid</td>
<td>0.34%</td>
<td>0.40%</td>
<td>0.34%</td>
<td>0.30%</td>
<td>0.41%</td>
</tr>
<tr>
<td>CMX CMX fid</td>
<td>0.42%</td>
<td>0.30%</td>
<td>0.23%</td>
<td>0.37%</td>
<td>0.32%</td>
</tr>
<tr>
<td>CMX + Track</td>
<td>0.82%</td>
<td>0.95%</td>
<td>0.80%</td>
<td>0.82%</td>
<td>0.84%</td>
</tr>
<tr>
<td>CMX only</td>
<td>0.11%</td>
<td>0.10%</td>
<td>0.16%</td>
<td>0.16%</td>
<td>0.15%</td>
</tr>
</tbody>
</table>

**Total Acc * Trig Eff ***

|                  | 7.78%   | 7.56%   | 6.97%   | 6.63%   | 5.94%   |

**Net Reconstructed**

|                  | 3.31%   | 3.23%   | 2.96%   | 2.83%   | 2.48%   |

N Expected:

|        | 6.6     | 12.3    | 21.7    | 45.2    | 89.2    |
Cross Section Limit

- Model-independent cross section limits for CHAMPs
  - no acceptance corrections
- VERY preliminary
- Not optimized

\[ \sigma(p p \rightarrow \tau_1 \tau_2) \] (pb)

DØ Run II Preliminary
L = 390 pb⁻¹

\[ \sigma(p p \rightarrow \tau_1 \tau_2) \] (pb)

95% CL (pb)

Mass (GeV)

CτOF Expected Limit (pb)Wele05c2, for Wele

Entries 139
Mean 160.6
RMS 41.23
- We expect a Stop mass limit above 220 GeV/c² 
  ➜ 95% CL
  ➜ not yet optimized
- High probability of discovery if stop mass below 200 GeV/c² 
  ➜ 5 sigma CL