Multi-muon events at CDF

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on behalf of the CDF collaboration

Rencontres de Moriond on
QCD and High Energy Interactions
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Physics motivation:

- puzzles in $b$ production and decays from Tevatron (Run I)
  - Correlated $b\bar{b}$ production, $\sigma_{bb}$, higher than Standard Model
  - Di-lepton invariant mass spectrum of $b$ cascade decays
  - Time-integrated mixing probability, $\chi$, of $b$-hadrons larger at Tevatron than at LEP

Recent results:

- new and very precise measurement of $\sigma_{bb}$ agrees with the prediction [PRD 77,072004 (2008)]


- Analysis leading to the excess of multi-muons
- Sources contributing to the multi-muon excess
- Additional properties of the multi-muon excess
**Correlated \( \bar{b}b \) cross section**

Two b’s in the central region with enough \( p_T \).

- Theoretical uncertainty (15%)

LO diagrams dominate

**Measurement techniques**

- Secondary vertex tagging
- Muon tagging

\[ R_{2b} = \frac{\sigma_{bb} \text{ (measured)}}{\sigma_{bb} \text{ (NLO)}} \quad \text{(RUN I)} \]

- Vertex tag analyses \( \rightarrow R_{2b} = 1 \)
- Muon tag analyses \( \rightarrow R_{2b} > 1 \)

\[ \sigma(p\bar{p} \rightarrow bb \rightarrow llX) > \sigma_{NLO} \]

Discrepancy \( \propto N(\mu) \)
Average time-integrated mixing probability, $\bar{\chi}$

Average time-integrated mixing probability of $b$ hadrons, $\bar{\chi}$ measured at the Tevatron is significantly larger than at LEP

$$0.152\pm0.013 \text{ vs } 0.126\pm0.004$$  \hspace{1cm} [PRD 69, 012002 (2004)]

$$\bar{\chi} = \frac{\Gamma(B^0 \rightarrow \bar{B}^0 \rightarrow l^+X)}{\Gamma(B \rightarrow l^\pm X)} = "\text{same sign}" \text{ "total"}, \ \Gamma^0 = B^0_d \text{ or } B^0_s$$

$$\bar{\chi} = \chi_d f_d + \chi_s f_s$$

Time integrated mixing parameters $\chi_d$ and $\chi_s$ well measured

Measurement of $\bar{\chi}$ constrains the fractions, $f_d$ and $f_s$, of $b$ quark fragmenting into $B_d$ and $B_s$

PDG: the $b$-hadron mixtures must be different
**Low mass di-leptons**

- **B enriched sample:**
  the low mass di-lepton invariant mass is not well modeled by sequential semi-leptonic decays of single $b$ quarks

- Simulation: HERWIG+EVTGEN

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**Event topology**

- **e, μ**, lep-jet
- **e^-, μ^-**, ν
- **μ^+, e^+**, ν
- away-jet
- SLT

**Invariant mass**

- $M (\text{GeV/c}^2)$

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**Opening angle**

- $\cos \theta$
New measurement of \( \sigma(p\bar{p} \rightarrow b\bar{b} \rightarrow \mu\mu X) \)

- Event sample: 743k events \( \rightarrow 742 \text{pb}^{-1} \)
  Defined by a dimuon trigger:
  - Central track with \( p_T > 3 \text{ GeV}, |\eta| < 0.7 \)
  - Match to stub in CMU and CMP (CMUP)
  - \( 5 < M_{\mu\mu} < 80 \text{ GeV} \) (no Z's, \( J/\psi, b \rightarrow c\mu \rightarrow \mu\mu X \))

- Known sources of real muons are:
  - \( b \rightarrow \mu \ (c\tau = 470 \mu\text{m}), c \rightarrow \mu \ (c\tau = 210 \mu\text{m}) \)
  - Prompt muons (Y, Drell-Yan)

- Known sources of fake muons include:
  - Hadrons punching through calorimeter
  - Decays in flight (K\( \rightarrow \mu, \pi \rightarrow \mu \))
  - Fake muons can be from prompt or h.f. decays
New measurement of $\sigma_{bb}$: The method

- Extract the sample composition by fitting the observed $d_0$ distribution of the muons [2D fit - $d_0(\mu_1)$ vs $d_0(\mu_2)$] with the expected $d_0$ distributions of muons from various sources and for all the combination ($bb, cc, pp, bc, bp, cp$)
- Develop templates for h.f (MC) and Prompt ($Y$ from data)
New measurement of $\sigma_{bb}$: results

- Very accurate
- Appreciably smaller than Run I results

$\sigma_{bb} = 1328 \pm 209 \text{nb} \quad \text{NLO}$

$\sigma_{bb} = 1618 \pm 148 \text{nb} \quad \text{Data}$

$(p_T^b > 6\text{GeV} \quad |\eta|<1.0)$
Investigating the differences: tracking

The highest tracking precision is achieved using hits in the SVX II detector; in this way we can separate muons from $b$’s, $c$’s and prompt sources.

**SVX II (L00, L0, L1, L2, L3, L4)**

**Impact parameter resolution:**
- 230 $\mu$m (COT only tracks)
- 30 $\mu$m (COT + $\geq$ 3 SVX hits)

The excellent modeling of the 2 muons impact parameter distribution is obtained only using:
- **tight SVX** requirements (hits in L0, L00 and two of the remaining L1-L4 layers)
- L0 and L00 are essential

This selection requires that both muons originate inside the beam pipe.
**Tracking differences**

- Analyses in CDF use **loose SVX** requirements: 3/8(SVX+ISL) layers
  - Muons can originate as far as 10.8 cm from the beam line
- Run I analyses selected muons originating from distances as large as 5.7 cm from the beam pipe
- According to simulation, 96% of QCD events have 2 muons originating inside the beam pipe

➢ Verifying the acceptance of the different Silicon req’s:

Use cosmic rays overlapping $pp$ collisions:
- 2 muons back to back clustering along the diagonal of $d_0(\mu_1)$ vs $d_0(\mu_2)$

After cosmic ray removal $\varphi_{\mu^-\mu^+} < 3.135 rad$
SVX selection efficiency

- Evaluate efficiencies using control samples of data
  - Prompt: (25.7±0.4)% using Y and Drell-Yan
  - Heavy Flavor: (23.7±0.1)% using $B \rightarrow J/\psi$, $B \rightarrow J/\psi K$, $B \rightarrow \mu D^0$

- From the sample composition determined in the $\sigma_{bb}$, the expected average efficiency of the tight SVX requirement:
  \[ \varepsilon_{\text{tight \ SVX}} = (24.4\pm0.2)\% \]
  Measured to be $(19.30\pm0.04)\%$ in the dimuon sample

- Efficiency of loose SVX requirements (using Y and $J/\psi$):
  \[ \varepsilon_{\text{loose \ SVX}} = (88\pm1)\% \]

- What do we conclude?
  - more background in the total sample (before SVX requirements)
  - Background is suppressed with the tight SVX selection
    $\rightarrow$ no hits in the first 2 silicon layers $\rightarrow$ large impact parameter
  - Background is not removed with looser SVX selection
    since it appears at large $d_0$
QCD events

Assume that the tight SVX selection isolates only known sources of dimuon events: we call this sample QCD

Is that reasonable?

- Charm contribution minimal for \(d_0 > 0.12\) cm
- Fit \(d_0\) distribution for muons with \(0.12 < d_0 < 0.4\) cm
  - Measure \(c\tau = 469.7\pm1.3\) µm (stat. error only)
  - PDG average \(b\) lifetime: \(c\tau = 470.1\pm2.7\) µm
- Reasonable assumption

Conclude that:

- QCD sample (selected with tight cuts) not significantly affected by additional background
- \(b\) contribution almost fully exhausted for \(d_0 > 0.5\) cm
The unexpected background: Ghost events

- Start with the total sample of dimuons
- We call Ghost events the excess of events that does not pass the tight SVX requirements after accounting for the tight SVX efficiency
  - Sample definition:
    - $\text{QCD} = \text{sum of contributions determined by the fit of the } \bar{b}b \text{ cross section analysis } [b, c, \text{prompts}]$
    - $\text{GHOST} = \text{All Dimuons} − \text{QCD}/\varepsilon_{\text{tight SVX}}$
QCD sources of dimuons have $d_0 < 0.5$ cm

Ghost events have much larger impact parameters

Using loose Silicon requirements

Impact parameter distribution of trigger muons

QCD vs Ghost events

- Ghost
- QCD

0.2 cm

$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$

$0$
$0.5$
$1$
$1.5$
$2$

$d$ (cm)

Muons/(0.008 cm)

- QCD sources of dimuons have $d_0 < 0.5$ cm
- Ghost events have much larger impact parameters
### Counting events (742pb⁻¹)

**Ghost = “All” − “QCD”**

<table>
<thead>
<tr>
<th>Type</th>
<th>Total</th>
<th>Tight SVX</th>
<th>Loose SVX</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>743006</td>
<td>143743</td>
<td>590970</td>
</tr>
<tr>
<td>All OS</td>
<td>98218</td>
<td>392020</td>
<td></td>
</tr>
<tr>
<td>All SS</td>
<td>45525</td>
<td>198950</td>
<td></td>
</tr>
<tr>
<td>QCD</td>
<td>143743 /$\epsilon_{\text{tight}}$ = 589111 ± 4829</td>
<td>143743</td>
<td>143743*$/\epsilon_{\text{loose}}$/$/\epsilon_{\text{tight}}$ = 518417 ± 7264</td>
</tr>
<tr>
<td>Ghost</td>
<td>153895 ± 4829</td>
<td>0</td>
<td>72553 ± 7264</td>
</tr>
<tr>
<td>QCD OS</td>
<td>98218</td>
<td>354228 ± 4963</td>
<td></td>
</tr>
<tr>
<td>QCD SS</td>
<td>45525</td>
<td>164188 ± 2301</td>
<td></td>
</tr>
<tr>
<td>Ghost OS</td>
<td>0</td>
<td>37792 ± 4963</td>
<td></td>
</tr>
<tr>
<td>Ghost SS</td>
<td>0</td>
<td>34762 ± 2301</td>
<td></td>
</tr>
</tbody>
</table>

**bb sample consists of 221564 ±11615 events without SVX request (194976±10458 bb events with loose SVX) – Ghost events : 154K!**
Plausible explanation to previous puzzles

- $\sigma_{bb}$ puzzle:

  Previous measurements use selection criteria:

  - close to “loose SVX”: ghost sample ~ 73K events compared to bb of ~195K \[ R \approx 1.3 \]
  - no SVX req’s at all: ghost sample ~ 150K events compared to bb of ~220K \[ R \approx 2 \]

  The general observation is that:

  As SVX req’s are made looser, the $\sigma_{bb}$ measurements increase together with the increase of the ghost sample contribution

- $\bar{\kappa}$ puzzle:

  Ghost sample splits equally in OS and SS events
  $\bar{\kappa}$ is measured from the ratio of SS/total using loose SVX req’s
Ghost events: possible sources

✓ No dependence on luminosity, run-periods etc

Ordinary sources of events that could give rise to real or fake muons with large $d_0$ that miss the innermost silicon layers:

1. Mis-measured tracks
2. Hadrons mimicking a muon (punch-through)
   evaluated with data using $D^0 \rightarrow K\pi$
3. Decays in-flight of $K^\pm, \pi^\pm \rightarrow \mu^\pm \nu_\mu$
   evaluated using Monte Carlo (Herwig)
4. Decays of long–lived hadrons:
   $K^0_S \rightarrow \pi^+\pi^- \quad \Lambda \rightarrow p\pi$
   evaluated using data
5. Secondary interactions in detector material
   secondary products with large $d_0$

We can explain 50% of the total ghost sample (153895 evts)
Ordinary sources of Ghost events

1. **Track mismeasurements: (many checks)**

   Look at events with \( \mu^+ + D^0 \rightarrow K^\pm \pi^\mp \)

   Events mainly due to \( b\bar{b} \)

   Combinatorics for \( D^0 \):

   - **Right:** \( \mu, K \) have same charge
   - **Wrong:** \( \mu, K \) have opposite charge

   ✓ No long tails in \( d_0(\mu) \) - consistent as coming from B’s

     ➢ Wrong sign comb. show the low level of fakes

2. **Hadronic punch-through – fake muons:**

   Measure probability per track that a \( \pi \) or K will punch–through the calorimeter

   Reconstruct \( D^{*+} \rightarrow D^0 \pi^+ \)

   with \( D^0 \rightarrow K^- \pi^+ \)

   ➢ \( D^{*+} \) uniquely identifies \( \pi, K \)

   Measure the rate hadrons are found as muons
Ordinary sources of Ghost events

3. **Decays-in-flight:**
   - Measure the probability that K and π decays produce CMUP muons (trigger muons) using generic hard scattering MC simulation [Herwig].
   - Probability per track that a hadron yields a trigger muon is \( \pi : 0.07\% \) \( K : 0.34\% \)
   - Normalize this rate from Herwig MC to measured \( bb \) cross section

   **Prediction:** 57000 of ghost events due to decays-in-light

   - Large uncertainty on prediction: (particle fractions, momentum spectra, \( \sigma_{bb} \), ...)

Yield of in-flight decays explains more than 35% of the ghost sample

However, only 10% of the decays-in-flight have \( d_0 > 0.5 \text{ cm} \)
Ordinary sources of ghost events

4. \(K_S^0\) and hyperon decays:
   - Look for \(\mu^+\) track with track \(p_T > 0.5\) GeV/c
   - Assume \(\mu\) and track are \(\pi\)
   - Kinematic acceptance \(\times\) reconstruction efficiency \(\sim 50\%\) (MC)

   - Approximately 12000 ghost events (8\%) are due to these decays

\[ (5348 \pm 225) \quad K_S^0 \]
\[ (678 \pm 60) \quad \Lambda \rightarrow \pi^- p \]

\(K_S^0\) Populate large \(d_0\)
Ordinary sources of ghost events

5. **Secondary Interactions:**
   
   • Look for \( \mu + \) tracks with track \( p_T > 0.5 \) GeV/c
   
   • Tracks in a \( 40^\circ \) cone around the muon
   
   ➢ Looking at the radius of the two tracks intersection vertex we should find spikes where there is concentrated material:

   Simulation:
   
   ![Simulation](image1)

   No visible spikes of multi-prong secondary interactions

   ➢ We can not exclude contribution to ghost events from elastic or quasi-elastic nuclear scattering in the detector material

   ![Ghost](image2)

   ![QCD](image3)
Search for additional muons:

Interesting for several reasons

- Events due to secondary interactions or decays-in-flight are not expected to contain significant amount of additional muons.
- If ghost events were like normal QCD events with some mismeasured trigger muons, the rate of additional muons should be as in QCD events.
- The excess of the low mass dileptons from Run I might be related to ghost events.
- Events with additional muons should be contributed mainly by $b$-sequential decays. Expect a contribution from muons faked by hadrons which is not simulated but is estimated from data.
Search for additional muons:

- **Look for additional muons:**
  Around each trigger muon
  Use all central muon detectors (CMU+CMP+CMX)
  Require initially $M_{\mu\mu} < 5 \text{ GeV/c}^2$
  - Requirements designed for maximal acceptance at the cost of higher fake rate

- **In data, 9.7% of the events contain an additional muons**
  1. Check the yield of additional muons in some class of events:
     - $Y(1S)$ events: 0.9% with an additional muon (fakes from underlying event)
     - $K^0_S$ events: 1.7% with an additional muon (mostly fakes)
  2. Check the efficiency of tight SVX req’s on trigger muons:
     - Expect it to rise from $\varepsilon_{\text{tight SVX}} = 0.193 \rightarrow 0.244$ expected for QCD
     - Instead it is found lower: 0.166 !
       - The ghost event contribution increases from 20.9% to 32%

- **Ghost events contain more additional muons than QCD events**
Low mass dimuons

Compare invariant mass in data and simulation that includes fakes

Tight SVX:
- Data: $6935\pm154$
- MC: $6998\pm239$

Entire sample: no SVX req’s:
- Excellent agreement on the $J/\psi$ prediction
- Clear excess at low mass not seen with tight SVX associated with ghost

Excess: $8451 \pm 1274$ evts

Conclusion: well understood
Extra muon/tracks in ghost events

Most of the additional muons in ghost events are within a cone of $\cos \theta > 0.8$ around the trigger muon

- Count tracks ($p_T > 2$ GeV/c, $|\eta| \leq 1.1$) inside cones
  
  Yield of charged tracks in ghost events $2 \times$ the one in QCD

- Count muons inside cones (Ghost events)
  
  After accounting for fakes there are approximately 9.4% real muon combinations with SS or OS charge compared to 2.1% in QCD evts.
  
  Yield of additional muons in ghost events $4 \times$ the one in QCD evts
Muon multiplicity in a $\cos \theta > 0.8$ cone

Plot shows the number of additional muons in a single cone (fake subtracted)

We count additional muons relative to the trigger muon:

$$M = N_{\text{OS}} + 10N_{\text{SS}}$$

$\forall$ OS $\mu$: $M = +1$

$\forall$ SS $\mu$: $M = +10$

For example:
in a cone of $\mu^+$ we find $2\mu^-$ and $1\mu^+$:
It corresponds to bin 12

First surprise!

Some ghost events have very large muon multiplicities - 3 or 4 muons in a cone
The impact parameter of the additional muons is consistent with that of initial muons - large tail.
Additional CMUP muons in ghost events

- The salient features of ghost events, like additional track and muon multiplicity higher than that of QCD events, remain even when requiring the additional muon to be CMUP (very pure)

- The large impact parameter distribution of additional muons is consistent with the trigger muons
Conclusions

- We observed an excess of events in the dimuon trigger sample that we do not understand, called Ghosts.
- The size of the excess is comparable to the $bb$ contribution.
- They offer a plausible explanation of all the previously observed inconsistencies and puzzles that have affected measurements of $b$-quark production and decay at the Tevatron for more than a decade.
- A piece of the ghost sample contains events with some unique properties which we can not explain and we are not yet able to rule out known processes:
  - contain high muon and track multiplicity
  - The additional muons exhibit large impact parameter well above the one of additional muons in the QCD sample.
- Contrary to the unexpected features of the ghost sample we understand very well the QCD sample in terms of detector, reconstruction and physics.
Event display

\[ E_t = 141.7 \]
Backup
Silicon efficiency

- Silicon efficiency from QCD simulation

\[ \varepsilon = (24.4 \pm 0.2)\% \]

- Tight SVX selection

\[ \varepsilon = (88 \pm 1)\% \]

- Loose SVX selection
Tracks reconstructed with hits in at least 20 layers of the central tracker are considered good.

- Use $Y \rightarrow \mu^+\mu^-$ where muon tracks have no silicon hits.
- Distribution exhausts after 0.12cm
  - Impact parameter distribution of muons in ghost events is not due to tracks reconstructed with no silicon hits

Resolution: 230 \( \mu m \)
Tracking quality – Using $K^0_S$

- Use $K^0_S \rightarrow \pi^+\pi^-$ reconstructed in the dimuon sample
- Use tracks with $p_T > 0.5$ GeV/c, $|\eta| < 1.1$ and opening angle $< 60^0$
- 3-d vertex constraint and correct the $L_{xy}$ for the Lorentz boost
- Fit of $L_{xy}$ returns a lifetime of 89.5ps
Additional muons by detector type

- Compare the fractional distribution of additional muons according to the detector type the muon was identified.
- Compare to QCD expectations where we predict the rates of additional muons.

<table>
<thead>
<tr>
<th>Sample</th>
<th>CMUP</th>
<th>CMU</th>
<th>CMP</th>
<th>CMX</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>17.0±0.4</td>
<td>53.0±0.7</td>
<td>26.0±0.5</td>
<td>4.0±0.2</td>
</tr>
<tr>
<td>Ghost</td>
<td>14.0±0.8</td>
<td>60.0±1.4</td>
<td>24±1</td>
<td>2.0±0.4</td>
</tr>
</tbody>
</table>

➢ The response of the muon detector is an unlikely candidate to explain the large excess of additional muons in ghost events.
Heavy flavor with large Lorentz boost

- It is counterintuitive to have heavy flavor with large boost and large $d_0$
- Use all dimuons (no mass cut).
Additional muon – remove low mass requirement

Search for additional muons without an invariant mass cut requirement
Combine the additional muon with the trigger muon of opposite sign if the two trigger muons have opposite charge (OSO)
For same sign initial dimuons combine the additional muon randomly (SSO and SSS)

Observation:
Additional muons are within a cone of $\cos \theta > 0.8$ around the trigger muon
Extra muon/tracks in ghost events – No low mass cut

- There are 1131090 QCD evts and 295481 ghost evts
  
  • Count tracks ($p_T > 2$ GeV/c, $|\eta| \leq 1.1$) inside cones

<table>
<thead>
<tr>
<th>Topology</th>
<th>All</th>
<th>SVX</th>
<th>QCD</th>
<th>$F_{QCD}$</th>
<th>Ghost</th>
<th>$F_{ghost}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>1315451</td>
<td>207344</td>
<td>849770 ± 6965</td>
<td>0.75</td>
<td>465860 ± 6965</td>
<td>1.58</td>
</tr>
<tr>
<td>SS</td>
<td>893750</td>
<td>140238</td>
<td>574745 ± 4711</td>
<td>0.51</td>
<td>318004 ± 4711</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Yield of charged tracks in ghost events $2 \times$ the one in QCD

• Count muons inside cones (Ghost events)

<table>
<thead>
<tr>
<th>Topology</th>
<th>QCD</th>
<th>Ghost</th>
<th>$F_K$</th>
<th>$F_\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>54545±447</td>
<td>28692 ± 447</td>
<td>15447 ± 210</td>
<td>9649 ± 131</td>
</tr>
<tr>
<td>SS</td>
<td>30053±246</td>
<td>20180 ± 246</td>
<td>10282 ± 137</td>
<td>6427 ± 81</td>
</tr>
</tbody>
</table>

After accounting for fakes there are approximately 28000 real muon combinations with SS or OS charge (9.4%) compared to 24492 (2.1%) for QCD evts.

Yield of additional muons in ghost events $4 \times$ the one in QCD evts (2.1%)
Correlated punch-through

- Traditionally searches for soft muons performed by CDF estimate the fake muon contribution using a per-track probability.
- It has been argued that ghost events could be due to a breakdown of this method in presence of events with high $E_T$ jets with many tracks not contained in the calorimeters. It could be true but there is no control sample to study it.
- Tightening selection criteria, features remain in the cost of reduced acceptance.
- We would have observed this effect also in the QCD control sample since the energy flow in the jet is similar.

**Track $\sum p_T$ in cones of $\cos \theta > 0.8$ around a trigger muon**
Cone correlations

≥ 2µ in both cones

Ghost Events

27790 ± 761 cones with ≥2µ \hspace{1cm} (1)

4133 ± 263 cones with ≥ 3µ

3016 with ≥ 2µ in both cones \hspace{1cm} (2)

Ratio of (2)/(1) = 0.11
comparable to what expected for double parton production (jets)
Ghost events with $\geq 2\mu$ in both cones

- Mass of all muons

- Mass of all tracks
Effect of Trigger bias on $d_0$ distributions - $K^0_S$ case

- Use $K^0_S \rightarrow \pi^+\pi^-$
- One $\pi$ punches through the calorimeter and gives the trigger muon (CMUP)
- Look for an additional track with $p_T > 2$ GeV/c in $40^0$ around the trigger muon
- Distribution of $d_0$ for trigger muon and track after side-band subtraction
Testing the lifetime hypothesis

Search for pairs of tracks in a cone of $\cos\theta > 0.8$ around a trigger muon with $p_T > 1$ GeV and opposite charge.
Fraction of the ghost events is due to an object $h_1$ that is produced with transverse momentum much larger than its mass and decays into 8 taus.

- Remove fakes assuming tracks are $\pi$
- Histogram corresponds to a toy MC of $8 \tau \to \mu$ with branching fraction 17.4% and $\varepsilon_{\mu}^{\text{trig}} = 50\%$ and $\varepsilon_{\mu}^{\text{add.}} = 83.8\%$.
- Assume $\varepsilon_{\text{kin.}} = 1$
- Toy MC of $4 \tau^+ - 4 \tau^+$ normalized to the data for bins $\geq 11$.
- Accounts for approximately 5% of the ghost events (13200 events).
Barbieri et al. [arXiv:0902.2145]

\[ O_5 = \frac{1}{\Lambda} (\bar{q} q) |\phi|^2 \quad p\bar{p} \rightarrow \phi\phi \]

\[ \phi \rightarrow 2\phi_1 \rightarrow 4\phi_2 \rightarrow 8\tau \]

\[ m_\phi = 15 \text{GeV} \]

\[ \phi_2 \rightarrow \tau \bar{\tau} \quad \text{with a long lifetime} \]
Run 1 – $\bar{\chi}$

- Muons could originate as far as 5.4 cm