Precise Calibration of the D0 LAr Calorimeter or Pileup, Noise and High Energy Calorimetry
(in the context of the D0 W mass measurement)

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Last year I discussed the D0 $W$ boson mass measurement with $4.3 \text{ fb}^{-1}$ of integrated luminosity.

Determined by likelihood fit to the measured $m_T$ and $p_T^e$ distributions as a function of $M_W$ hypothesis.

The measurement consists in a precise understanding of two components: the electron cluster and the hadronic recoil.

Both measured in the U-LAr sampling calorimeter.

The Challenge

Electron energy scale needs to be known at the level of 0.01%.

Hadronic energy scale needs to be known at the level of 1%.

This year we will discuss specific challenges from pileup in the recoil energy reconstruction (low energy hadronic energy $\approx 5$ GeV).
The problem of pileup

Pileup became fashionable in the LHC experiments, but it is also a problem at the Tevatron.

The instantaneous luminosity at the Tevatron is significantly lower than at the LHC.

But it is achieved with much larger bunch spacing.

Cramming a lot of protons and anti-protons in a single bunch.

The challenge, part 2

Despite not being very commented, pileup, both in-time and out-of-time is also a non-negligible effect at the Tevatron.
Noise suppression

Although the effect of pileup is important, we not always measure the pileup energy, what makes it difficult to model its effect (cluster reconstruction inefficiency, underlying energy in the electron cluster, …)

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\sigma$ (ADC counts)</th>
<th>$\sigma$ (MeV)</th>
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</thead>
<tbody>
<tr>
<td>CC-EM1</td>
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<tr>
<td>EC-EM1</td>
<td>3.2</td>
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<tr>
<td>CC-EM3</td>
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</table>

- Cells below $1.5\sigma$ are discarded.
- Cells below $2.5\sigma$ are not used for reconstruction.
- Cells above $2.5\sigma$ but below $4.0\sigma$ are also not used for reconstruction, unless neighbor of another cell above $4.0\sigma$ (T42.5 algorithm).

The huge and unnecessary $4\sigma$ noise suppression has a non-trivial impact on, e.g., low energy cells in the periphery of electron clusters and on soft hadronic activity. In many cases, all the information we really have is not pileup, but noise width.
Example of undesired consequence

Measure underlying energy inside the electron cluster

- Important source of non-linearity in the calorimeter response at high luminosity.
- Tradionally modeled using “rotated clusters”.
- Large noise suppression makes the correlation weaker.

- Example for End Calorimeter electron clusters
- Average visible energy in rotated clusters (high SET): $\approx 400$ MeV
- Average underlying energy in the electron cluster (high SET): $\approx 600$ MeV
Unsuppressed Zero-Bias (ZB) overlay

Trying to model the pileup using “first principle” tuned descriptions is not precise enough to perform precision measurement like the $W$ boson mass.

The idea

- Do not simulate additional $p\bar{p}$ interactions from first principles.
- Routinely collect ZB events triggered only using the accelerator clock sequentially in all bunch crossings positions in the beam. For this trigger do not noise suppress the calorimeter signal, i.e., read all cells!
- **Overlay** one of these data events on each simulated event (hard scatter). For calorimetry, overlay that means adding cell by cell energies from the ZB events to the energies from the simulates events.

- Very powerful idea and one of the reasons why we are able to measure the $W$ mass at high instantaneous luminosity environments.
- **All** details from the calorimeter noise, readout and electronics are automatically included in the simulation.
- As well as pileup, of course…
Examples of tricky detector effects

- Baseline subtraction readout error (negative energies, above)
- Different length of readout cables ($\phi$ structure, left)
- Measurement of electric current in each cell to assess HV loss (discussed last year)
Effect of pileup on the detection of soft hadronic activity

\[ \vec{u}_T = \vec{u}_{T\text{ HARD}} + \vec{u}_{T\text{ SOFT}} + \vec{u}_{T\text{ ELEC}} + \vec{u}_{T\text{ FSR}} \]

- The ZB energy can help other contributions to the recoil vector to be visible.
- Therefore, to correct simulate the effect of, eg., hard recoil, we simulate \( Z \rightarrow \nu\nu \) events with unsup ZB overlay...
- ... and, after noise suppression, we subtract the ZB energy again.
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Also true for the other components

- $\vec{u}_T^{FSR}$: Out-of-cluster FSR photons. Simulate single photons with unsup ZB overlay and, after reconstruction, subtract cell by cell the ZB energy.

- $\vec{u}_T^{ELEC} = \vec{u}_T^{UE} + \vec{u}_T^{LEAK}$: Leakage is modeled by simulation of single electrons with unsup ZB overlay and, after reconstruction, remove the ZB and electron energies.

In the End Calorimeters, where the UE activity is larger and the cluster smaller, the ZB energy creates visible leakage of the electron shower into the recoil system for all electron cluster!
Consequences of pileup in our measurement

Visible loss of $E_T$ resolution

Blue: Run 2a (low luminosity), Red: Run 2b (high luminosity and pileup)

- The $E_T$ observable loses a lot of power in the combination with $p_T^e$ and $m_T$ owning to the increased systematic uncertainties and it is not included in the D0 $W$ mass combination anymore (although still done for consistency checks).
- Long R&D necessary to understand pileup and the effect of ZB overlay and noise suppression. This is even more important in the final 10 fb$^{-1}$ that we are doing right now.
And (surprise!) increase of PDF uncertainty

- In principle, our main observable ($m_T$) is invariant over longitudinal boosts. In theory it should not be sensitive to PDF variations.
- But things are more complicated. The harsh acceptance cut we make in electron $\eta$ makes the distribution not invariant anymore.
- The same happens with the recoil resolution... fluctuations around the value that makes the observable perfectly invariant under longitudinal boosts create PDF sensitivity.
Projections of uncertainties

But we know how to beat the PDF uncertainty, main limitation of the $W$ mass measurement: include forward electrons (only D0 can currently do!)

<table>
<thead>
<tr>
<th>Source</th>
<th>Public. 2009 (1.0 fb$^{-1}$)</th>
<th>Public. 2012 (4.3 fb$^{-1}$)</th>
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<td>19</td>
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</tr>
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</table>

This idea has also been discussed here and we are on track for a publication in 2014!
Even the ILC prospects are not too much better than what we can do soon at the Tevatron!
Even the ILC prospects are not too much better than what we can do soon at the Tevatron! But a TLEP can smash the uncertainty down to 1-2 MeV, and that would be amazing!