First Observation of Diboson Production in Hadronic Final States at the Tevatron

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Why Dibosons? Why with Jets?

- Road to Higgs paved with dibosons!
  - $WW, WZ, ZZ$
    - Not previously observed in final states with jets at hadron colliders
  - Same final state as for low mass Higgs
    - $H+W/Z \rightarrow bb+\ell\nu/\nu\nu$
  - Small signals in large backgrounds
    - Test of analysis techniques
- Sensitive to new physics
How do You Find Dibosons?

- **Strategy:**
  - Select dijet events with large missing transverse energy (MET)
    - Sensitive to $\ell\nu$ and $\nu\nu$ decay modes
  - Maximal use of data to estimate backgrounds
  - Simple but smart analysis techniques
    - Focus on deep understanding of backgrounds
    - It’s never late to add multivariate techniques
How do You Find Dibosons?

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- Select dijet events with large missing transverse energy (MET)
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  - Focus on deep understanding of backgrounds
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Challenges:
- Need lots of data
- High efficiency triggers at all luminosities
  - L2 trigger upgrade
- Large backgrounds dominated by multijet events with fake MET and Z/W+jets
  - Sophisticated technique to suppress QCD multijets and estimate systematics
- Extracting small signal
Calorimeter Trigger Upgrade

- Trigger designed for $30 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$... Tevatron now regularly achieving $300 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$

- Upgraded L2 trigger
  - More sophisticated algorithm (almost same as in offline)
  - Better resolution and turn-on
  - Better performance at high luminosity
Backgrounds

Electroweak

- Use MC to describe kinematics
- $W$+jets
  - $W \rightarrow e\nu, \mu\nu, \tau\nu$
- $Z$+jets
  - $Z \rightarrow \nu\nu$
  - $Z \rightarrow e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}$
- Top quark pair production
Backgrounds

Electroweak

- Use MC to describe kinematics
- \( W + \text{jets} \)
  - \( W \rightarrow e\nu, \mu\nu, \tau\nu \)
- \( Z + \text{jets} \)
  - \( Z \rightarrow \nu\nu \)
  - \( Z \rightarrow ee, \mu\mu, \tau\tau \)

- Top quark pair production
Backgrounds

- **Electroweak**
  - Use MC to describe kinematics
  - $W+$jets
    - $W \rightarrow e\nu, \mu\nu, \tau\nu$
  - $Z+$jets
    - $Z \rightarrow \nu\nu$
    - $Z \rightarrow e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}$
  - Top quark pair production

- **QCD multijets**
  - Fake MET, but large rate
  - Reject as much as possible
  - Use data to model remainder

- **Non-collision (cosmics)**
  - Negligible after timing requirement

Diboson signal swamped by QCD background with fake MET

Jet 1
Jet 2
Jet n
Mis-measured jet tends to align with MET: $\Delta\phi$ should help rejection
MET Resolution Model (Metmodel)

- Example of jet energy resolution
  - Mis-measurements of jet energy are leading source of fake MET
  - Obtain jet energy resolution as a function of $E$ and $\eta$

- Select events with true MET:
  - Calculate MET-significance based on event configuration and known energy resolution
  - Use MET-significance to select events with true MET
Validation of Metmodel

- Use $W(\rightarrow e\nu) + \text{jet}$ data to validate MET-resolution

- Regions dominated by events with fake MET
  - Low MET-significance and small $\Delta\phi(\text{jet,MET})$
### Diboson Candidate Selection

| Variable         | Cut values          |
|------------------|---------------------|
| MET              | > 60 GeV            |
| Jet -1,2 $E_T$   | > 25 GeV            |
| Jet EmFr         | < 0.9               |
| Jet -1,2 $|\eta|$ | < 2.0               |
| $\Delta \phi_{\text{closest}}$ | > 0.4 rad          |
| MET-significance | > 4                 |
| $\Delta R_{\text{lep-jet}}$ | > 0.2               |
| $E^{EM}/E^{tot}$ | 0.3-0.85            |
| $M_{jj}$         | 40 GeV/c$^2$ – 160 GeV/c$^2$ |
| Jet timing      | < 4.5 ns            |

44,910 diboson candidate events after selection

QCD multijet rejection
Modeling Multijet Background

- Track MET (trkMET)
  - Analogous to MET
- True MET
  - Small $\Delta \varphi$(trkMET-MET)
- Fake MET
  - Large $\Delta \varphi$(trkMET-MET)

- Subtract EWK from data in $\Delta \varphi$(trkMET-MET) > 1.0 region
  - Address MC-data resolution and modeling effects with $Z \rightarrow \mu\mu$ events
  - EWK MC normalized to data in peak region
Checking Background Model

- Check distributions sensitive to fake MET
  - MET-significance
  - $\Delta \varphi(\text{jet}, \text{MET})$
- EWK background and signal have the same shapes in these variables
M$ _{jj}$ Templates: Multijet Background

- Shape & normalization (6144 events) taken from data in the region $\Delta \phi$(trkMET-MET) > 1.0 after EWK subtraction
  - Shape & normalization included as constraints in M$ _{jj}$ fit
- Uncertainties from extrapolation into $\Delta \phi$(trkMET-MET) < 1.0 region determined using dijet MC
M. Templates: EWK Background

- Shape taken from MC
- Total number of EWK events unconstrained in fit (~31000 expected)

| Process | Expected % of sample |
|---------|----------------------|
| $Z \rightarrow \nu \nu$ | 28.9 |
| $Z \rightarrow \tau \tau$ | 1.0 |
| $Z \rightarrow \mu \mu$ | 0.7 |
| $Z \rightarrow e e$ | 0.0 |
| $W \rightarrow \tau \nu$ | 24.1 |
| $W \rightarrow e \nu$ | 14.4 |
| $W \rightarrow \mu \nu$ | 12.8 |
| tt | 0.9 |
| Single top | 0.5 |
| Total | 83.3 |
Systematics on Shape of EWK

- Use data $\gamma$+jets as alternative template
  - Many uncertainties cancel (detector effects, ISR/FSR...)
- Kinematics of $V$+jets and $\gamma$+jets similar but not identical:

$$V + jets(data) \approx \frac{V + jets(MC)}{\gamma + jets(MC)} \times \gamma + jets(data)$$
M$_{jj}$ Templates: Signal

| Process | Expected % of sample |
|---------|----------------------|
| WW      | 2.2                  |
| WZ      | 0.7                  |
| ZZ      | 0.3                  |
| Total   | 3.2                  |

- Shape from MC
- Number of signal events unconstrained in fit (~1400 expected)
- Jet energy scale included as Gaussian constraint in fit
Systematics

| Systematic                  | % uncert. |
|-----------------------------|-----------|
| **Extraction**              |           |
| EWK shape                   | 7.7       |
| Resolution                  | 5.6       |
| **Total extraction**        | 9.5       |
| JES                         | 8.0       |
| JER                         | 0.7       |
| $E_T$ resolution model      | 1.0       |
| Trigger inefficiency        | 2.2       |
| ISR/FSR                     | 2.5       |
| PDF                         | 2.0       |
| **Total acceptance**        | 9.0       |
| Luminosity                  | 5.9       |
| **Total**                   | 14.4      |

Uncertainties on extraction

Additional uncertainties that contribute to cross section
Signal Extraction

- Fit result:
  - $1516 \pm 239\text{(stat.)} \pm 144\text{(syst.)}$
  - Expected $1398 \pm 243$

- Significance
  - Naively, $\frac{1516}{\sqrt{(239^2 + 144^2)}} = 5.4\sigma$
  - Consider parameter variations for all sources of systematics:
    - Compare likelihood of background only with full fit result
    - Convert difference into probability
  - Lowest significance returned: $5.3\sigma$
Cross Section

\[ \sigma = \frac{N_{VV} \, \text{(extracted)}}{A \times \varepsilon \times \mathcal{L}} \]

- \( N_{VV} \, \text{(extracted)} = 1516 \)
- Acceptance, \( A \): weighted by VV cross sections
- Efficiency, \( \varepsilon \):
  - Trigger: 96%
  - Cosmics removal: 99%
- Luminosity, \( \mathcal{L} \): 3450 pb\(^{-1}\)
- Cross section:
  - Measured: \( 18.0 \pm 2.8 \, \text{(stat.)} \pm 2.4 \, \text{(syst.)} \pm 1.1 \, \text{(lumi)} \) pb
  - SM prediction: \( 16.8 \pm 0.5 \) pb

| Process | Cross Section, pb | Acceptance, % |
|---------|-------------------|---------------|
| WW      | 11.7              | 2.48          |
| WZ      | 3.6               | 2.64          |
| ZZ      | 1.5               | 2.94          |
Summary

- First observation of vector boson pair production in hadronic final state at the Tevatron
  - Milestone in search for low mass Higgs
  - Developed and tested new effective techniques

- Measured diboson production cross section
  - Measured: $18.0 \pm 2.8\,\text{(stat.)} \pm 2.4\,\text{(syst.)} \pm 1.1\,\text{(lumi)}\,\text{pb}$
  - SM prediction: $16.8 \pm 0.5\,\text{pb}$

- Paper submitted to PRL
  - Available as arXiv:0905.4714
Extra Slides
Re-weighting $\gamma + \text{Jets}$

- Kinematics of photon+jets vs. W/Z + jets not IDENTICAL,
- however $\rightarrow$ weight the photon+jets data to the
- ratio of W/Z+jets / pho+jets MC
## Fit Results

| Source     | Nevents | Stat Uncert |
|------------|---------|-------------|
| Jes        | 0.985   | 0.019       |
| Ewk        | 36140   | 1230        |
| Jet bkg    | 7249    | 1130        |
| Signal     | 1516    | 239         |

| Source     | Jet slope | jes | ewk  | jet  | sig  |
|------------|-----------|-----|------|------|------|
| Jet slope  | 1         | 0.212 | -0.419 | 0.437 | 0.062 |
| jes        | 1         | -0.010 | 0.037  | -0.116 |
| Ewk        | 1         | -0.967 | -0.382 |
| Jet        | 1         |       | 0.206  |
| sig        |           |       |        | 1     |
Fit Results

| Floating parameter | Fitted value | Stat Uncert |
|--------------------|--------------|-------------|
| Jet slope          | 0.724        | 0.047       |
| jes                | 0.985        | 0.019       |
| Ewk                | 36140        | 1230        |
| Jet                | 7249         | 1130        |
| sig                | 1516         | 239         |

- Jet bkg background template (6144 events in peak and out, slope -0.02)
  - Jet slope ~20% uncertainty
  - Jet norm ~20% uncertainty
  - (0.724x-0.02) is the fit result
Cosmic Removal

- Relying on EM and HAD timing
  - $|\text{JET EM timing}| < 4.5\text{ns}$
  - $|\text{JET HAD timing}| < 15\text{ns}$
- Treat this as systematic uncertainty.
  - The final fit will lump this into EWK

$Z \rightarrow ll$ to measure efficiency

$\varepsilon = 98.9 \pm 0.2\%$

Data to estimate bkgd.

$B = 97 \pm 6$

Similar to EWK

$\chi^2 / \text{ndf} = 14.39 / 18$

Prob = 0.7031

$p_0 = 34.92 \pm 2.61$

$p_1 = -0.221 \pm 0.022$