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

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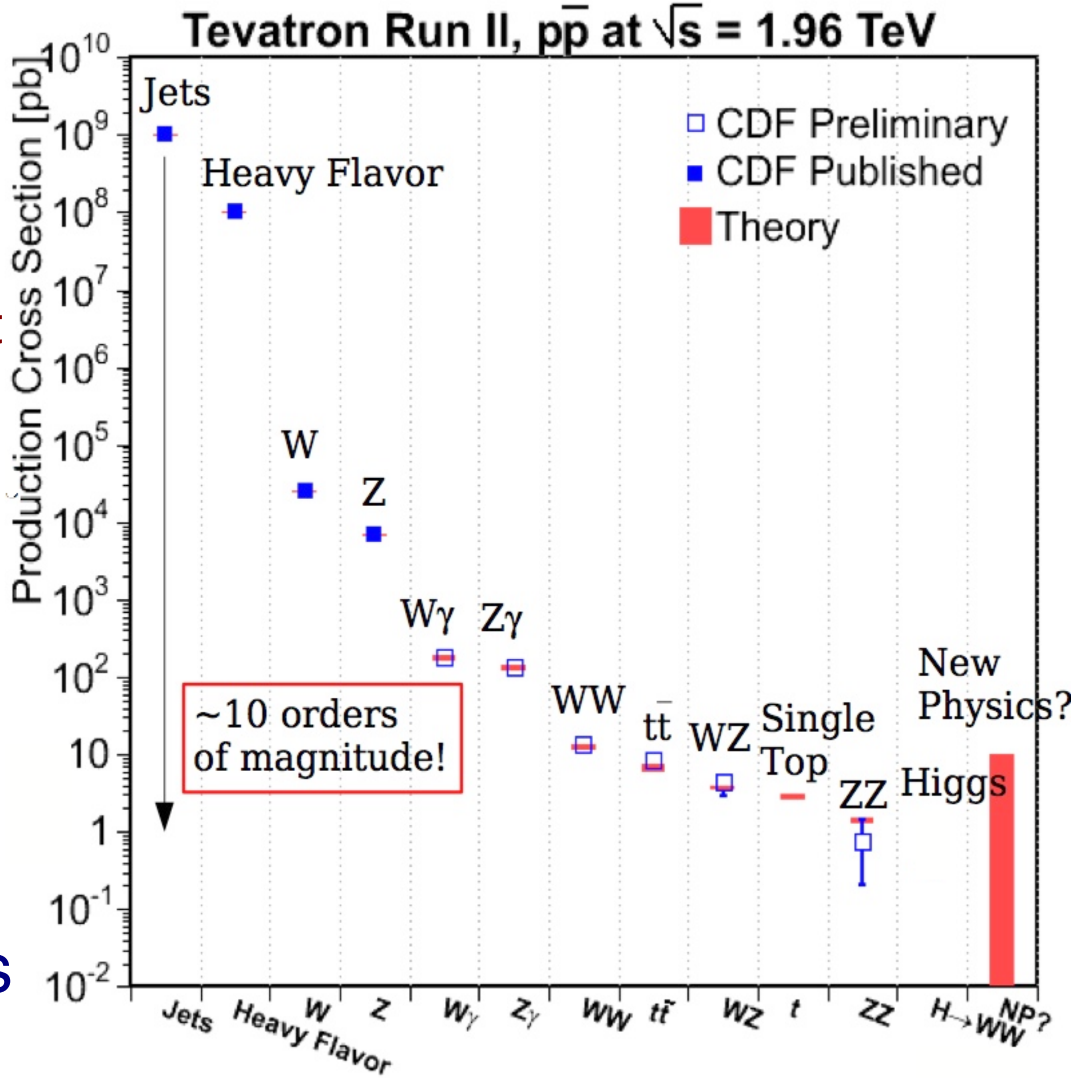
2009 Meeting of the Division of Particles and Fields of the American Physical Society

Wayne State University, July 27 - 31, 2009

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

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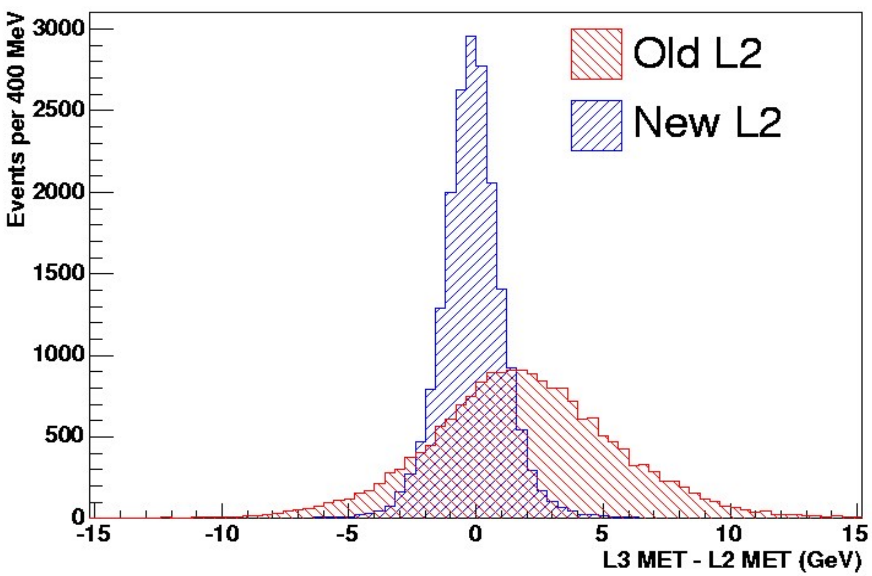
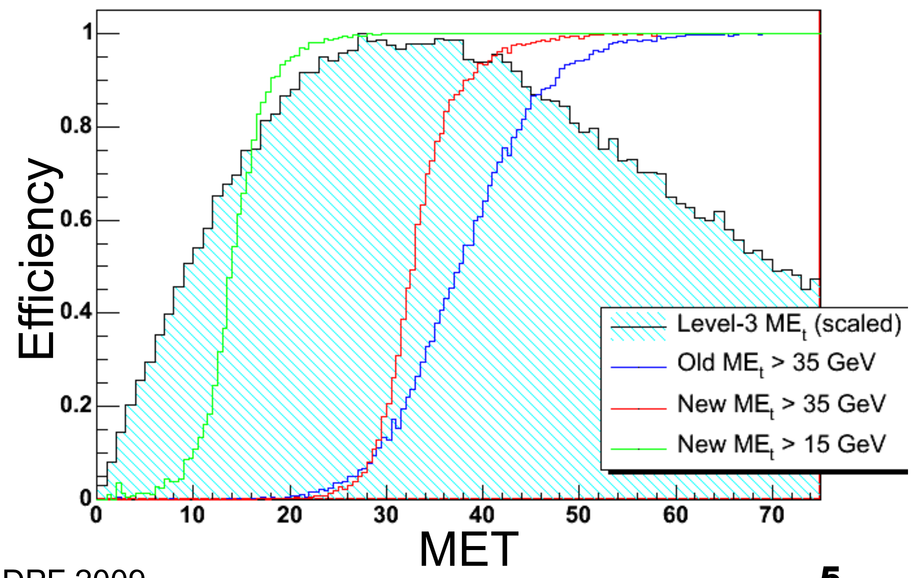
- Challenges:
  - Need lots of data
  - High efficiency triggers at all luminosities
    - L2 trigger upgrade
  - Large backgrounds dominated by multijet events with fake MET and Z/W+jets
    - Sophisticated technique to suppress QCD multijets and estimate systematics
  - Extracting small signal

Calorimeter Trigger Upgrade

- Trigger designed for $30 \times 10^{30} cm^{-2} s^{-1}$... Tevatron now regularly achieving $300 \times 10^{30} cm^{-2} s^{-1}$
- 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
    - $Z \rightarrow \nu\nu$
    - $Z \rightarrow ee, \mu\mu, \tau\tau$
  - Top quark pair production

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Dominant EWK backgrounds

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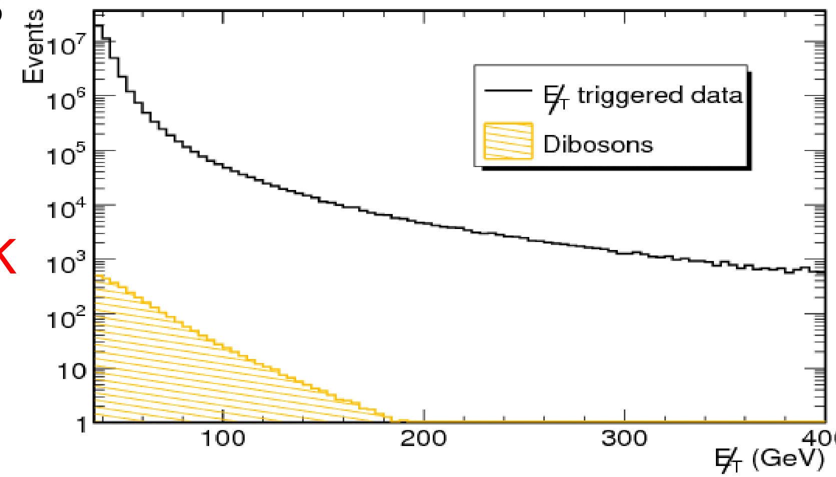
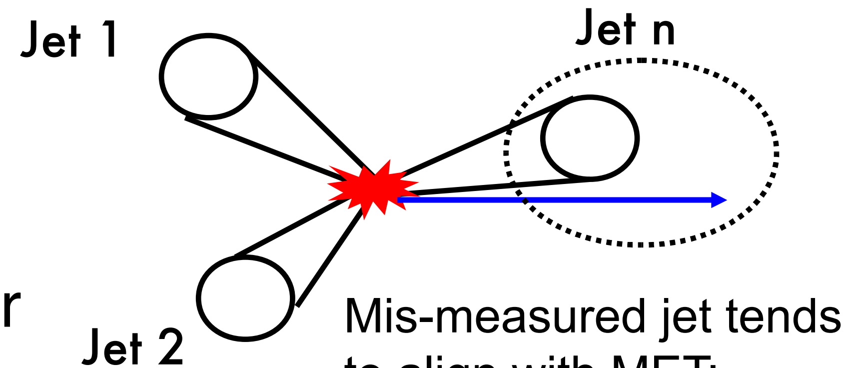
  - Z+jets
    - $Z \rightarrow \nu\nu$
    - $Z \rightarrow ee, \mu\mu, \tau\tau$
  - Top quark pair production
- QCD multijets
  - Fake MET, but large rate
  - Reject as much as possible
  - Use data to model remainder
- Non-collision (cosmics)
  - Negligible after timing requirement

Dominant EWK backgrounds

Diboson signal swamped by QCD background with fake MET

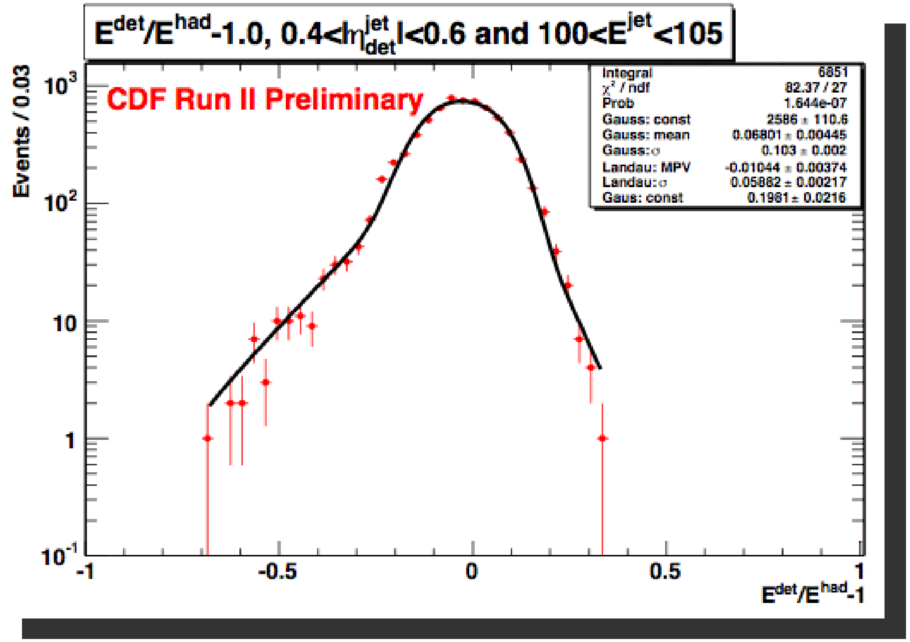




Mis-measured jet tends to align with MET: $\Delta\varphi$ should help rejection

MET Resolution Model (Metmodel)

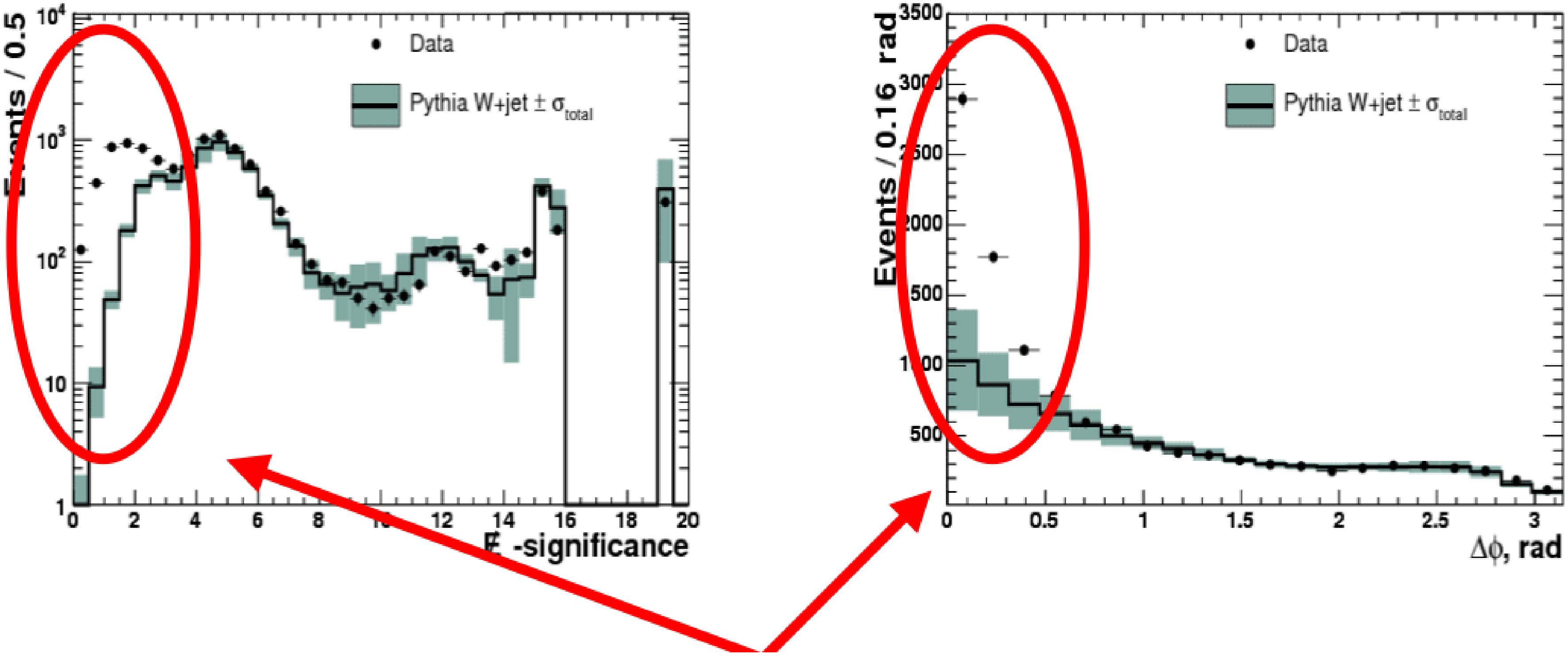
- Example of jet energy resolution
  - Mis-measurements of jet energy are leading source of fake MET
  - Obtain jet energy resolution as a function of E and η



- 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(→ eν) + jet data to validate MET-resolution



- Regions dominated by events with fake MET
  - Low MET-significance and small Δφ(jet,MET)

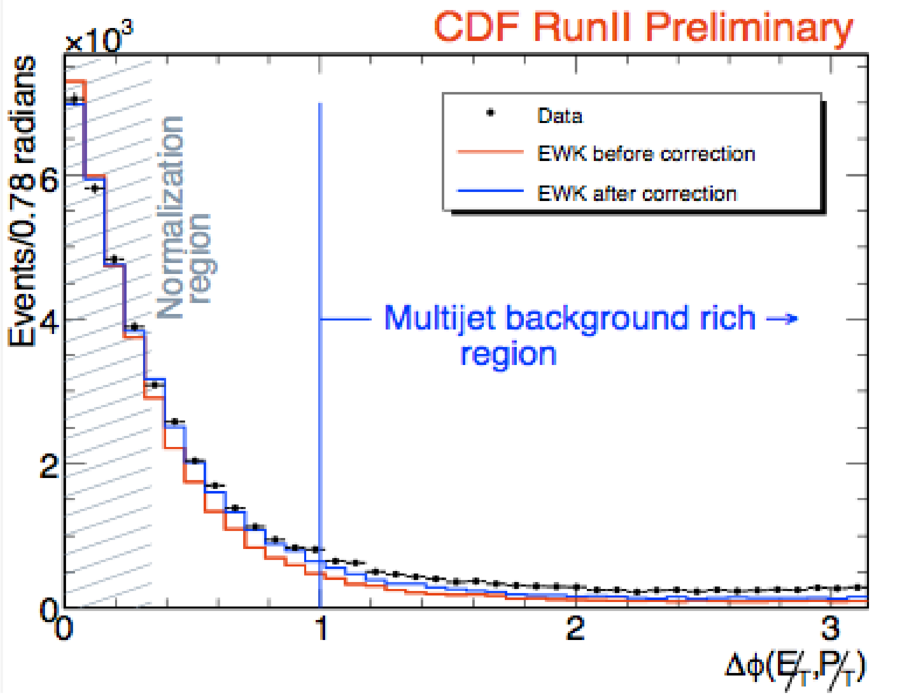
Diboson Candidate Selection

44910 diboson candidate events after selection

QCD multijet rejection

Variable	Cut values
MET	>60 GeV
Jet -1,2 E_T	>25 GeV
Jet EmFr	<0.9
Jet -1,2 $\|\eta\|$	<2.0
$\Delta\varphi_{closest}$	>0.4 rad
MET-significance	>4
$\Delta R_{lep\text{-}jet}$	>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

Modeling Multijet Background

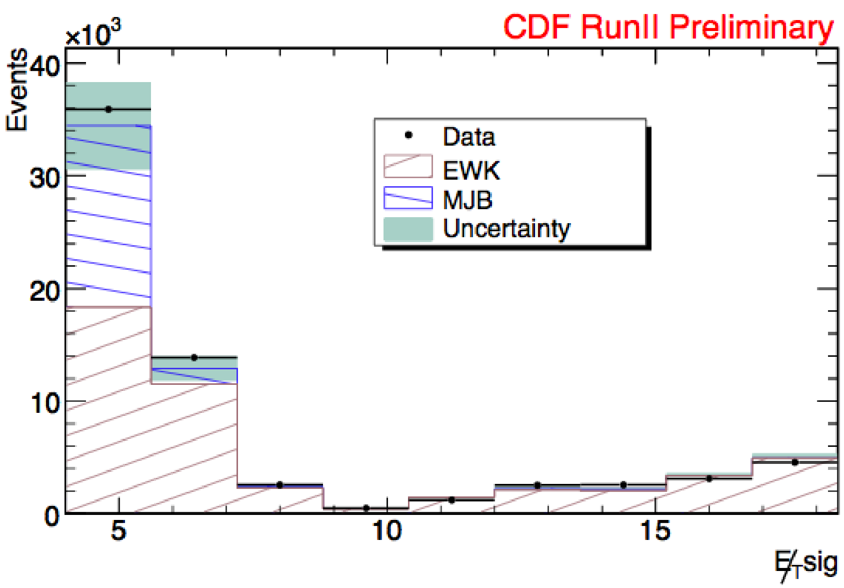


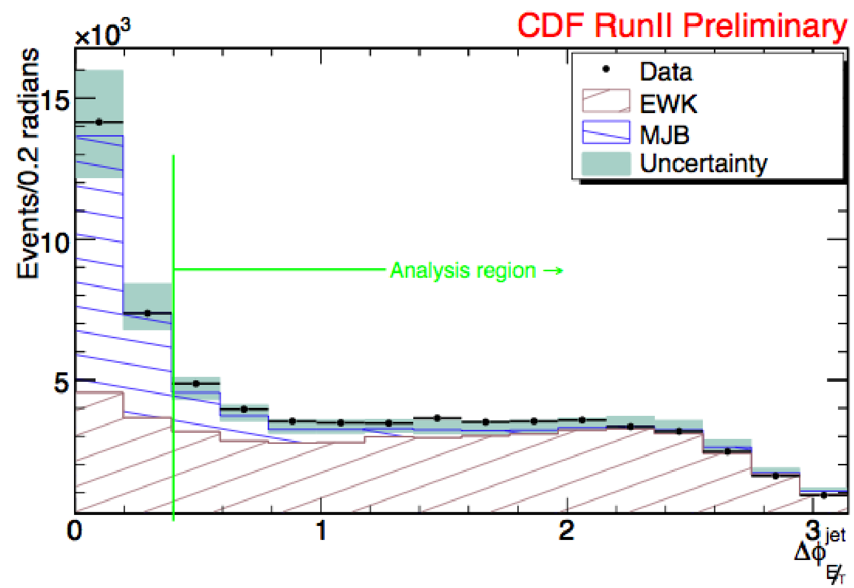
- Track MET (trkMET)
  - Analogous to MET
- True MET
  - Small $\Delta\varphi$(trkMET-MET)
- Fake MET
  - Large $\Delta\varphi$(trkMET-MET)

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

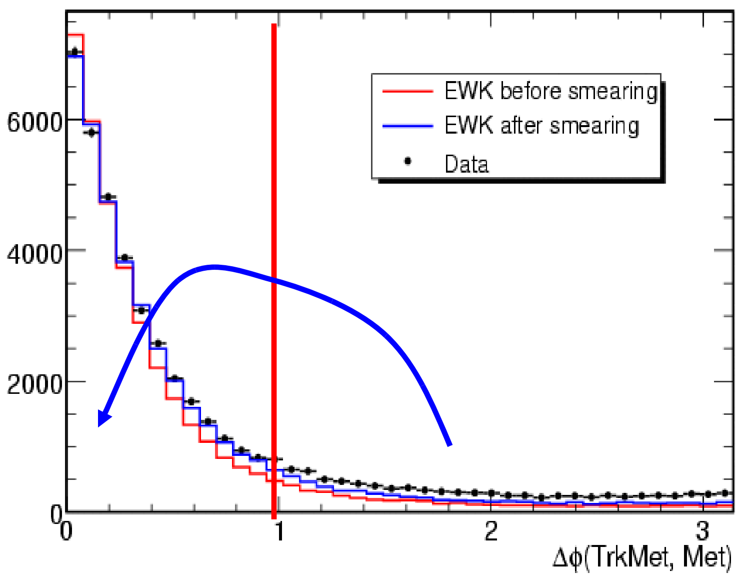
Checking Background Model

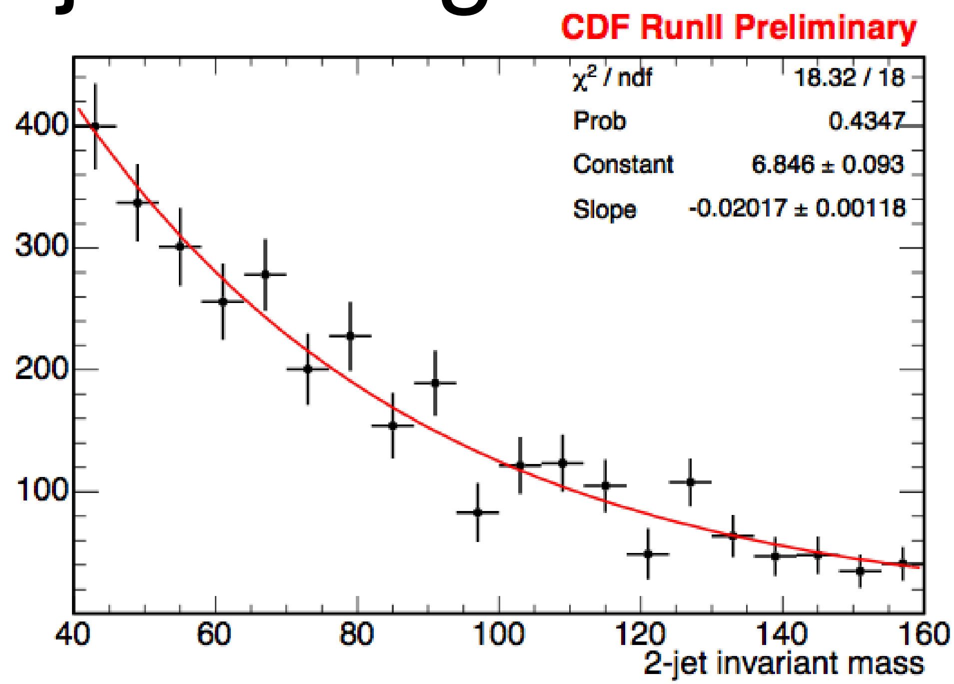
- Check distributions sensitive to fake MET
  - MET-significance
  - Δφ(jet,MET)
- EWK background and signal have the same shapes in these variables





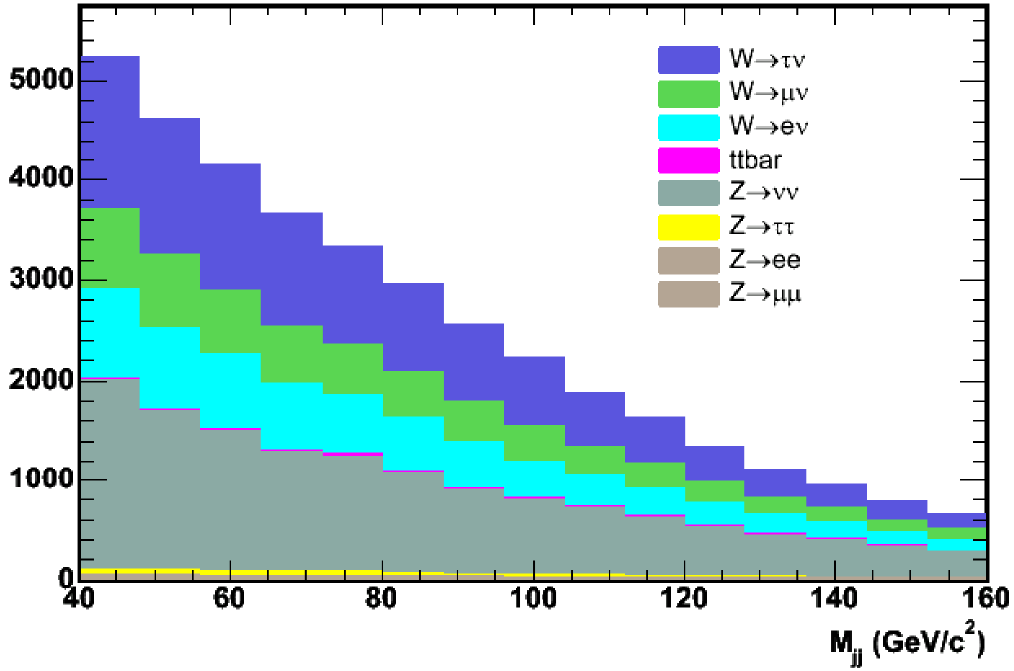
M_{jj} Templates: Multijet Background





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

M_{jj} Templates: EWK Background



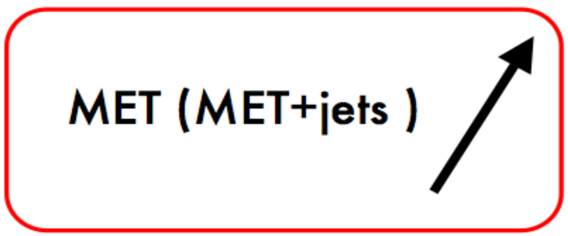
- Shape taken from MC
- Total number of EWK events unconstrained in fit (~31000 expected)

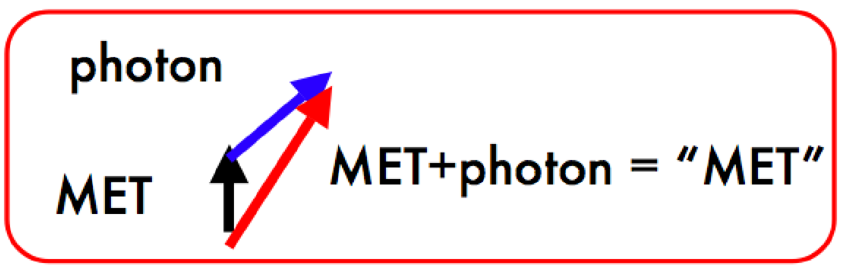
Process	Expected % of sample
Z→νν	28.9
Z→ττ	1.0
Z→μμ	0.7
Z→ee	0.0
W→τν	24.1
W→eν	14.4
W→μν	12.8
tt	0.9
Single top	0.5
Total	83.3

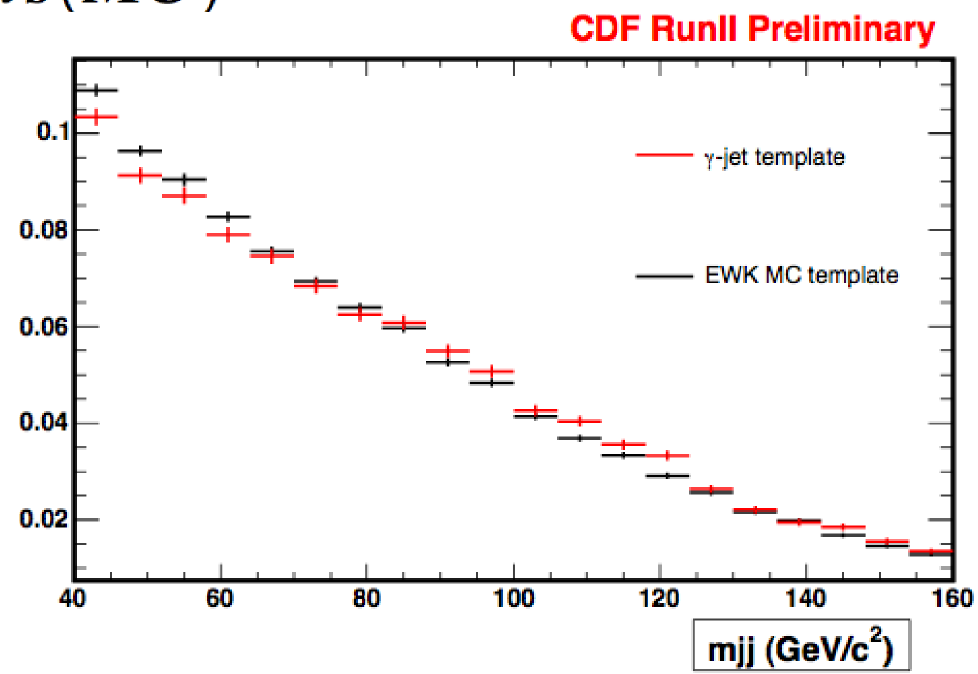
Systematics on Shape of EWK

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

$$V + jets(data) \approx \frac{V + jets(MC)}{\gamma + jets(MC)} \times \gamma + jets(data)$$

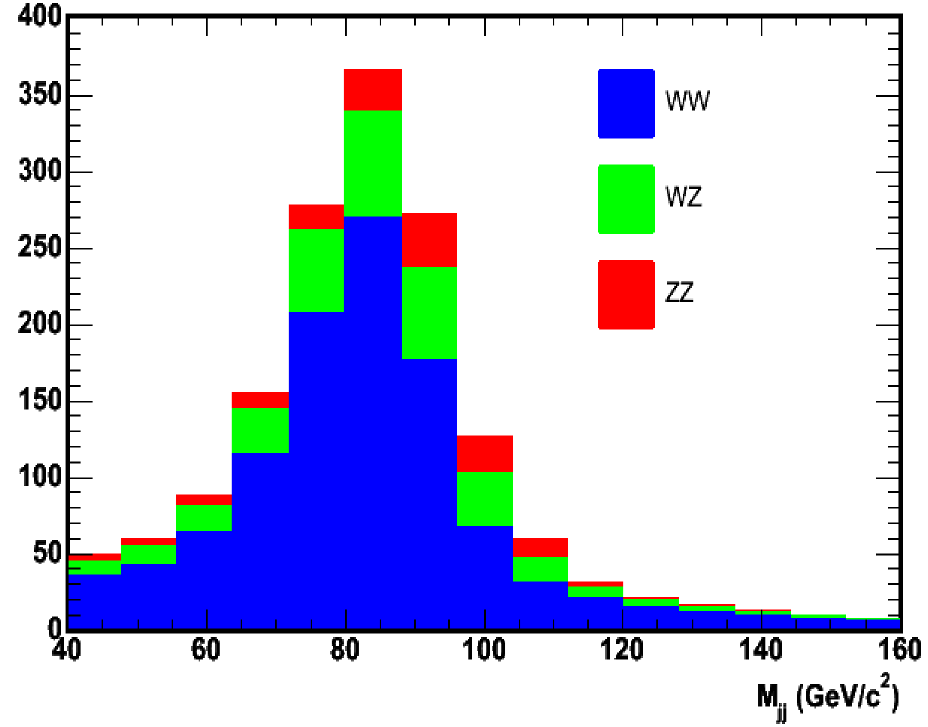






M_{jj} Templates: Signal

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

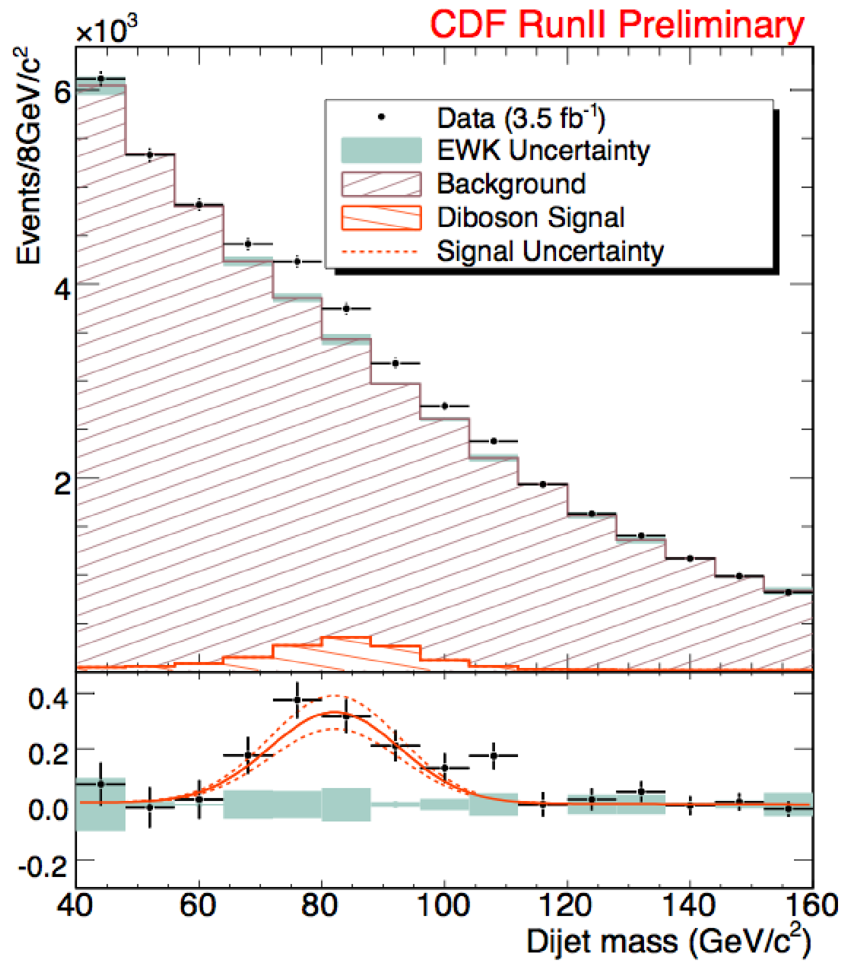
	Systematic	% uncert.
Extraction	EWK shape	7.7
	Resolution	5.6
	Total extraction	9.5
Acceptance	JES	8.0
	JER	0.7
	$\not{E}_T$ resolution model	1.0
	Trigger inefficiency	2.2
	ISR/FSR	2.5
	PDF	2.0
	Total acceptance	9.0
	Luminosity	5.9
	Total	14.4

Uncertainties on extraction

Additional uncertainties that contribute to cross section

Signal Extraction

- Fit result:
  - 1516 ± 239(stat.) ± 144(syst.)
  - Expected 1398 ± 243
- Significance
  - Naively, $1516/\sqrt{(239^2+144^2)}$ = 5.4σ
  - Consider parameter variations for all sources of systematics:
    - Compare likelihood of background only with full fit result
    - Convert difference into probability
  - Lowest significance returned: 5.3σ



Cross Section

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

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

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

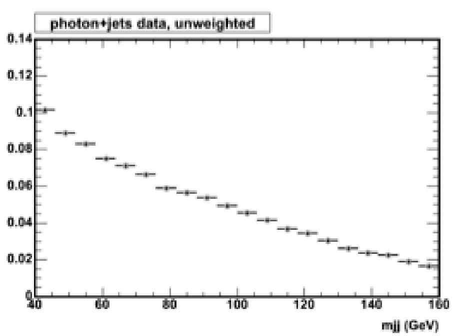
Summary

- 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 ± 2.8(stat.) ± 2.4(syst.) ± 1.1(lumi) pb
  - SM prediction: 16.8 ± 0.5 pb
- Paper submitted to PRL
  - Available as arXiv:0905.4714

Extra Slides

Re-weighting γ + Jets

- Kinematics of photon+jets vs. W/Z + jets not IDENTICAL,
- however → weight the photon+jets data to the
- ratio of W/Z+jets / pho+jets MC



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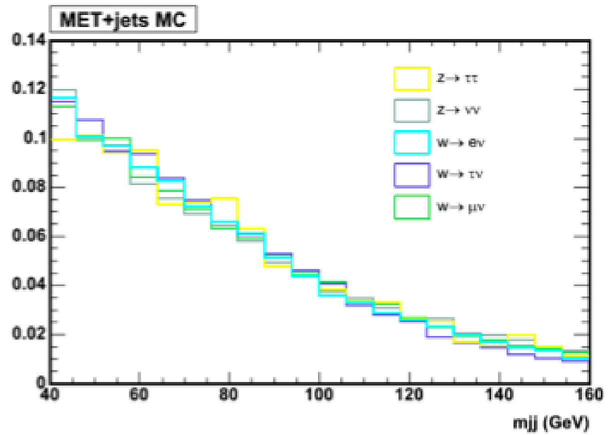

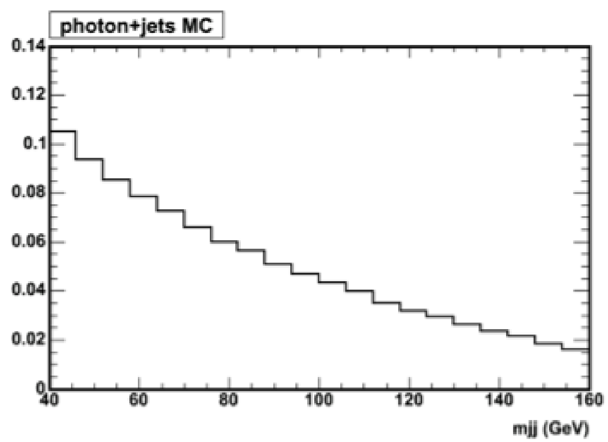

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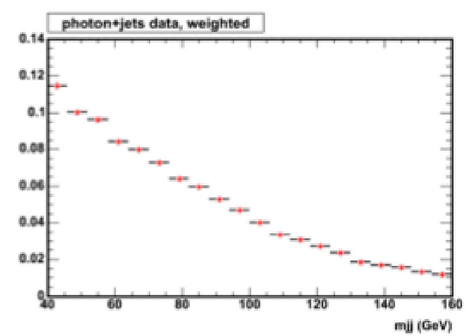


Fit Results

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

	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

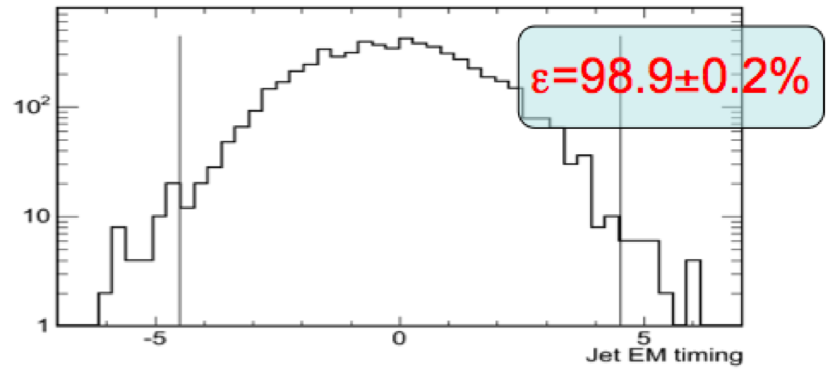
Floating parameter	Fitted value	Stat Uncert
Jet slope	0.724	0.047
jes	0.985	0.019
Ewk	36140	1230
Jet	7249	1130
sig	1516	239

- 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

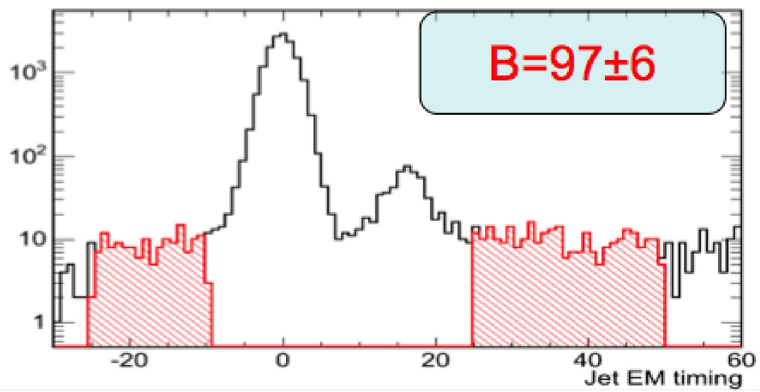
Cosmic Removal

- Relying on EM and HAD timing
  - |JET EM timing| < 4.5ns
  - |JET HAD timing| < 15ns
- Treat this as systematic uncert.
  - The final fit will lump this into EWK

Z→ll to measure efficiency



Data to estimate bckg.



Similar to EWK