First observation of vector boson pairs with hadrons at the Tevatron

Gene Flanagan

Purdue University

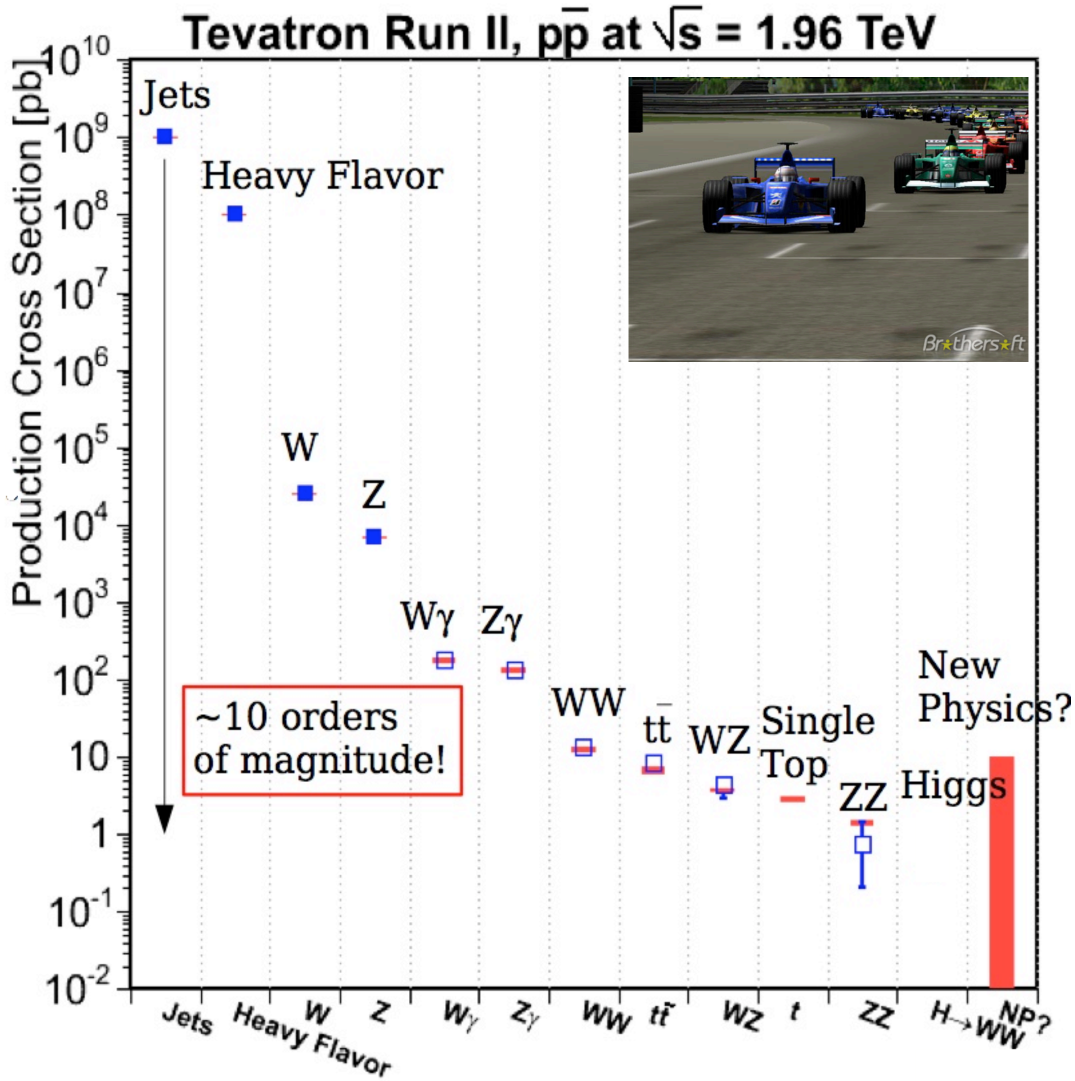
For the CDF collaboration

Road to Higgs paved with dibosons

Why dibosons ?

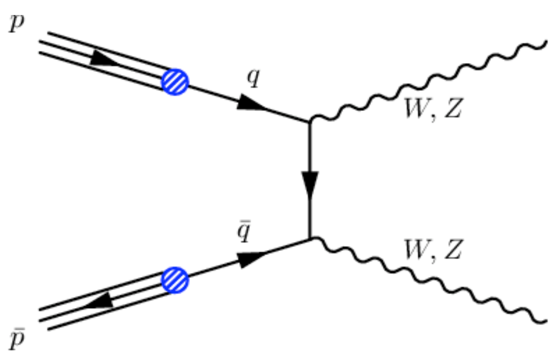
- Same final state as low mass Higgs channels
  - ZH,WH

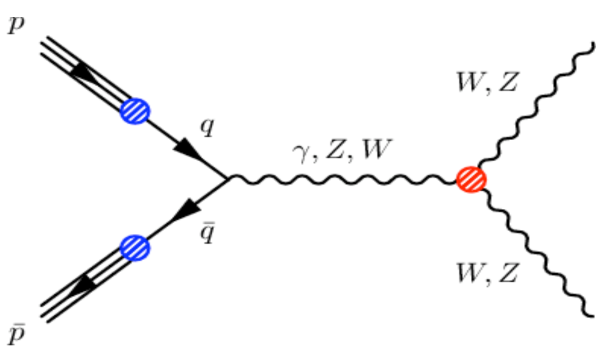
Small signals in a large backgrounds



How does the Standard Model stack up ?

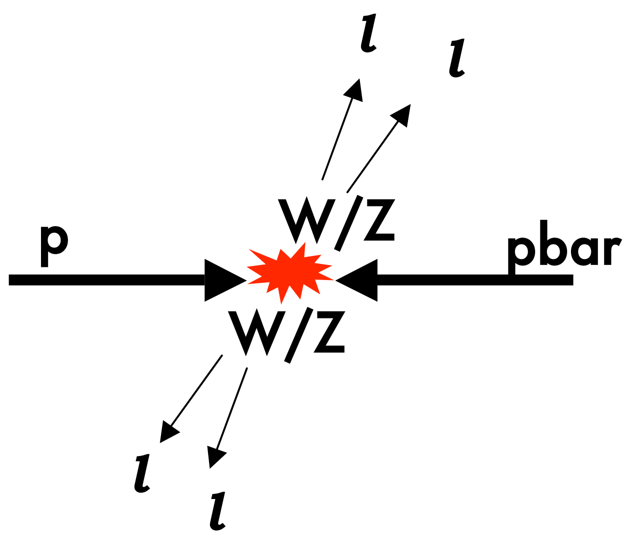
- The study of diboson production :
  - Provides a rich source of electroweak Standard Model tests
    - Cross sections
    - Kinematic distributions
    - Gauge boson couplings





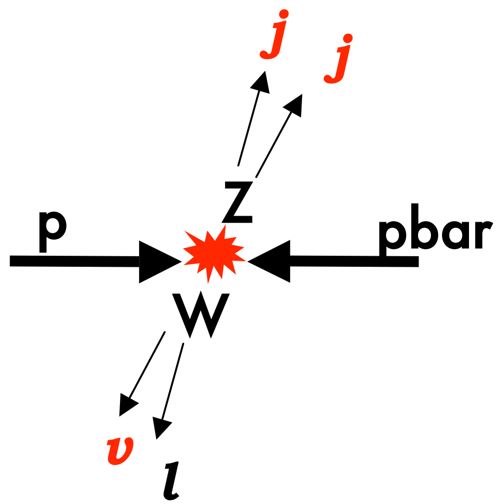
- Sensitive to new physics signatures

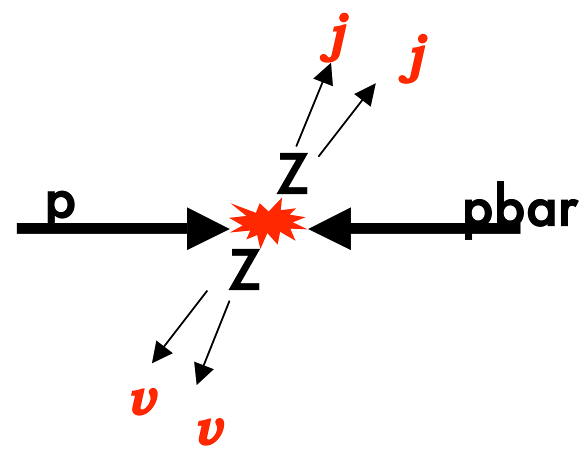
Diboson final states



- Already seen WW,WZ & ZZ production in leptonic final state
- Cross sections measurements
- Anomalous coupling results

- Today: hadronic final states





Method→ look for peak in dijet mass (M_{jj}) in events with large missing transverse energy (MET>60GeV) and 2 jets (E_T>25 GeV)

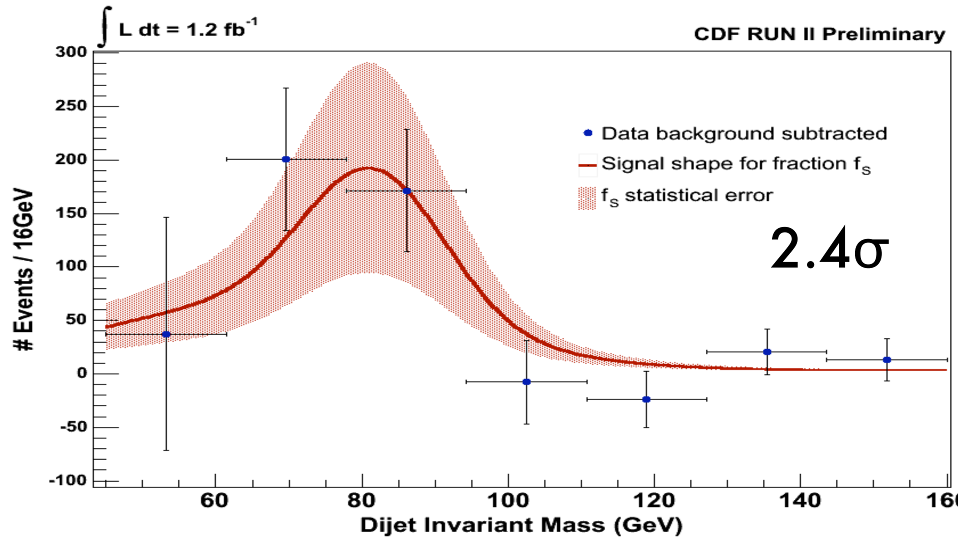
Recent Tevatron results

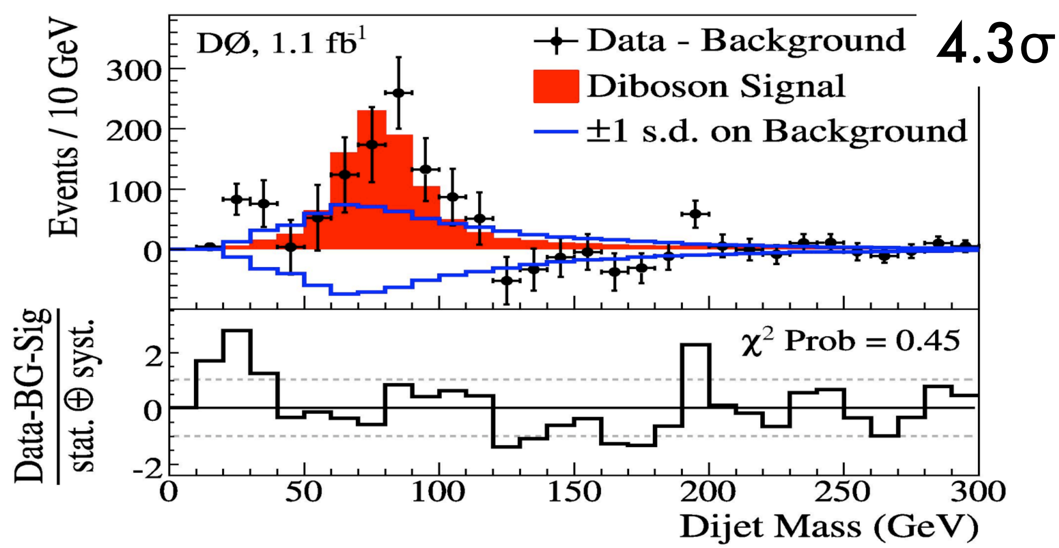
- Diboson production in lνjj(ννjj) not yet observed

  – CDF → 2.4σ in WW/WZ→lνjj

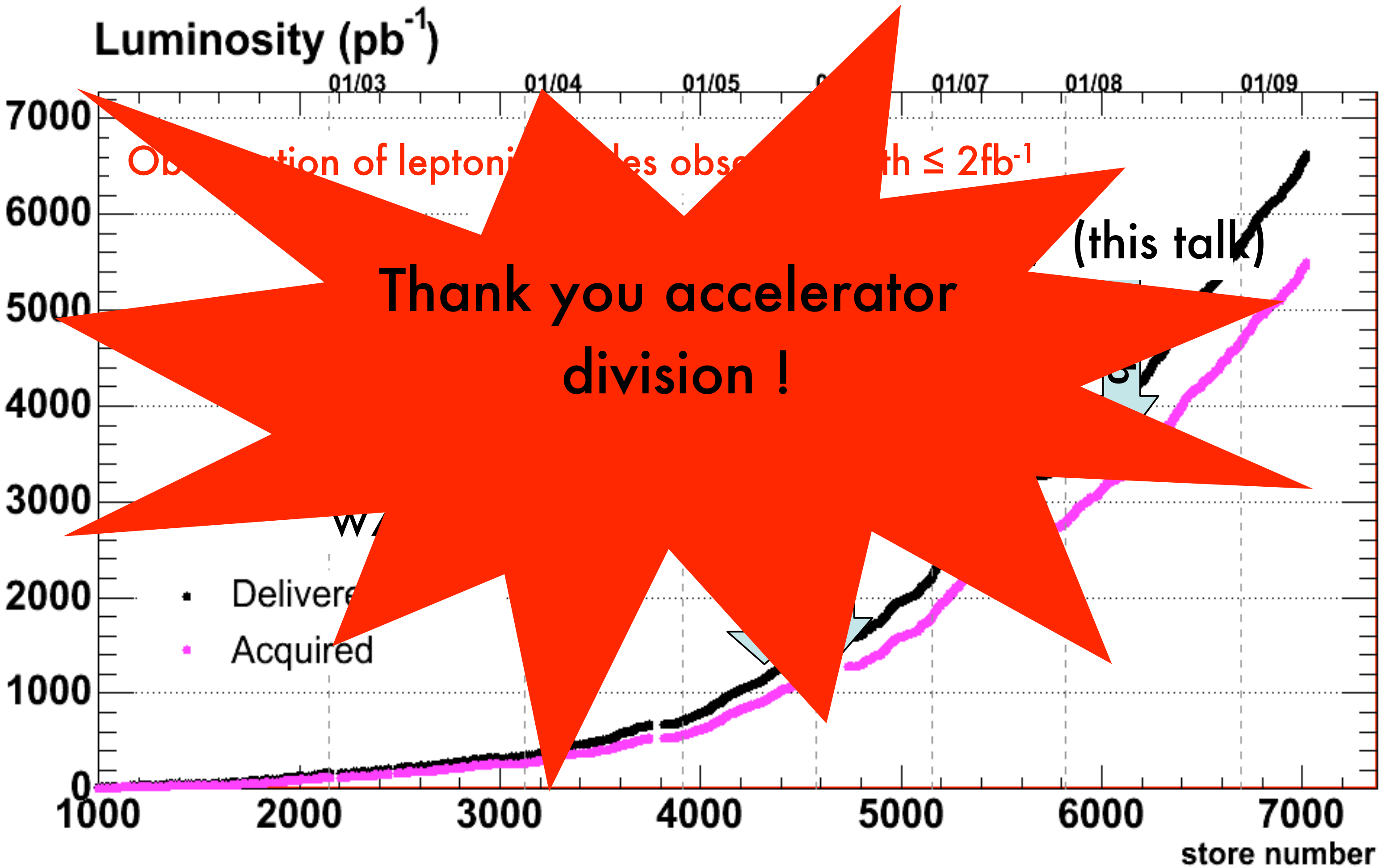
  – D0 → evidence for WW/WZ→lνjj

  – Exciting results in the pipeline





Dibosons at the Tevatron



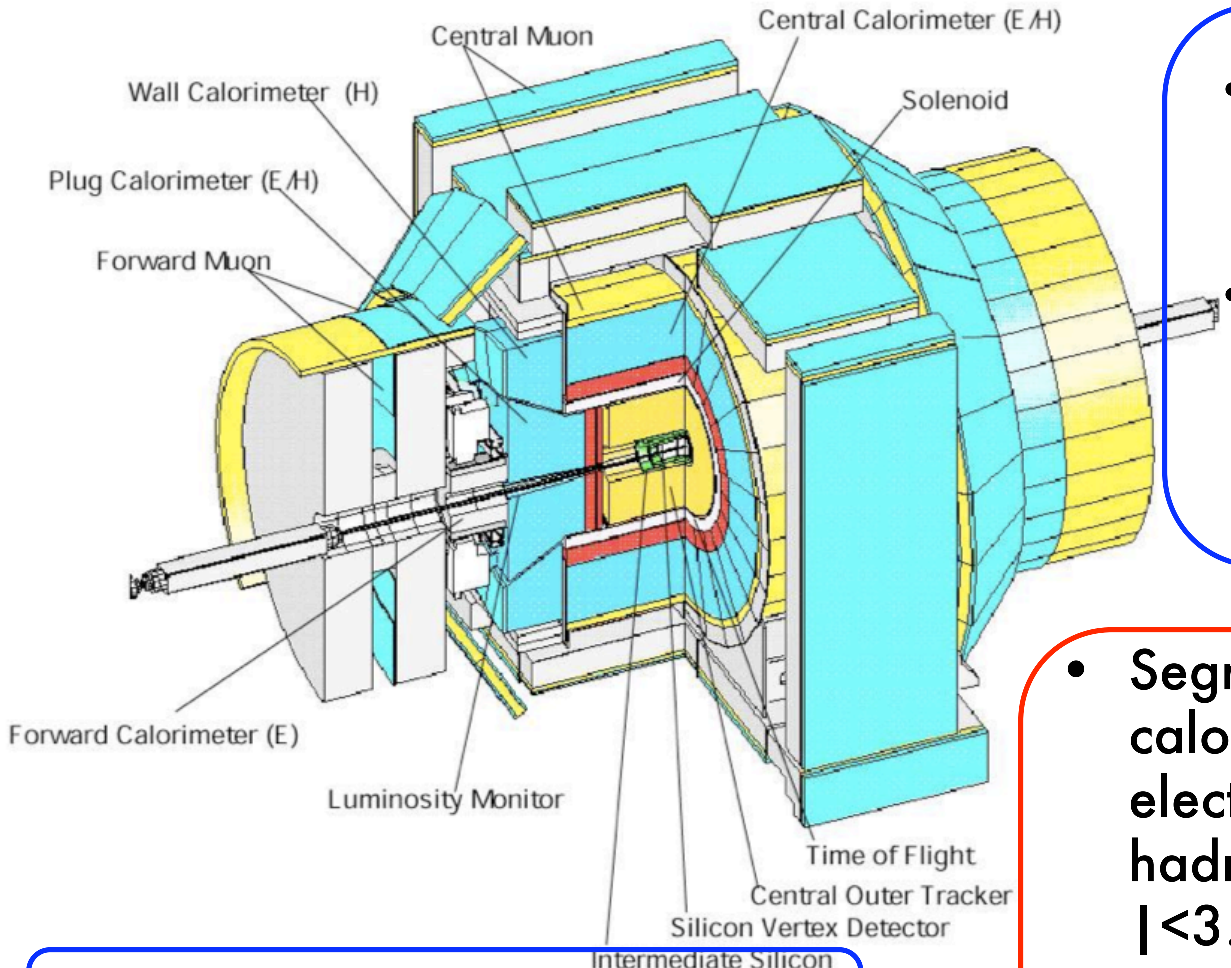
Combination of increasing datasets and analysis advancements producing impressive results, top, single top, higgs and dibosons

Challenges

Challenges of searching for dibosons in the MET+2jet signature:

- Technical/operational:
  - Need a lot of data
  - High purity and high efficiency triggers at all luminosity
- Analysis
  - Large background dominated by jet production and W/Z+jets
  - Extracting a small signal

The CDF II detector



- Silicon tracker allows precision vertex detection $|\eta|<2$
- Drift chamber $|\eta|<1$ measures charged particle P_T

- Muon detectors outside calorimeter

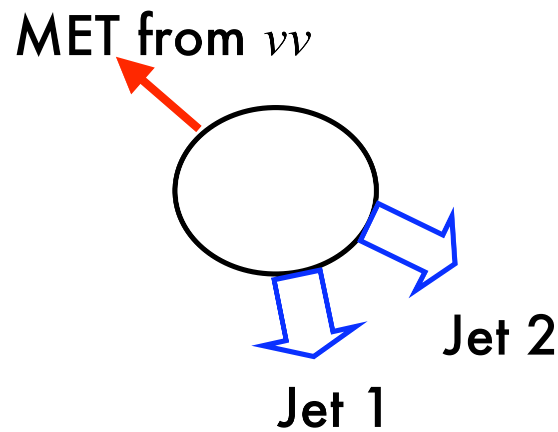
- Segmented sampling calorimeters: electromagnetic and hadronic compartments $|\eta|<3.6$
- Used to measure jets & missing transverse energy (MET)

Missing transverse energy (MET)

True MET (neutrinos)

- Energy flow imbalance in the transverse plane

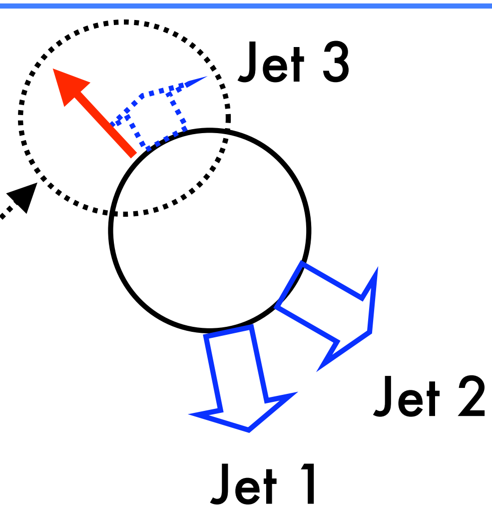
ZZ →$\nu\nu$jj example for real MET



Fake MET:

- Jet mis-measurement/resolution
- How a jet event can look like a VV → MET+2jets

Mis-measured jet
has MET associated with it



Challenges

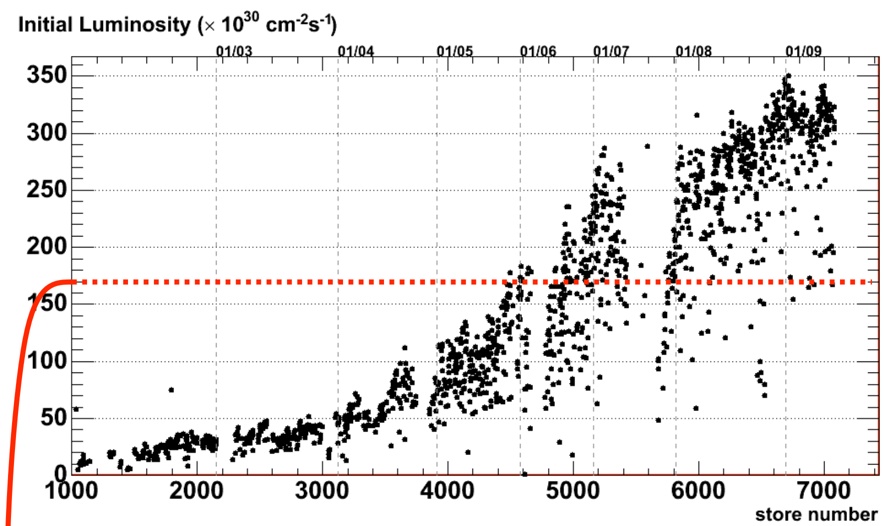
Challenges of searching for dibosons in the MET+2jet signature:

- Technical/operational:
  - Need a lot of data ✓
  - High purity and high efficiency triggers at all luminosities
- Analysis
  - Large background dominated by jet production and W/Z+jets
  - Extracting a small signal

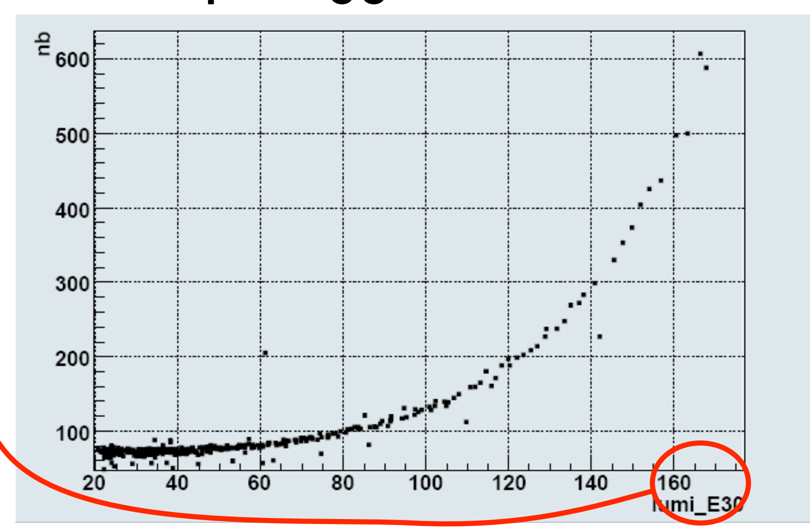
Triggering on dibosons

- Higher instantaneous luminosity
  → more interactions
  - more fake MET events being selected (poor resolution)
- MET trigger rates skyrocket
  - heavy prescaling, turning off triggers ?

To preserve MET + jet based physics program need to upgrade calorimeter trigger



MET+2jet trigger cross section

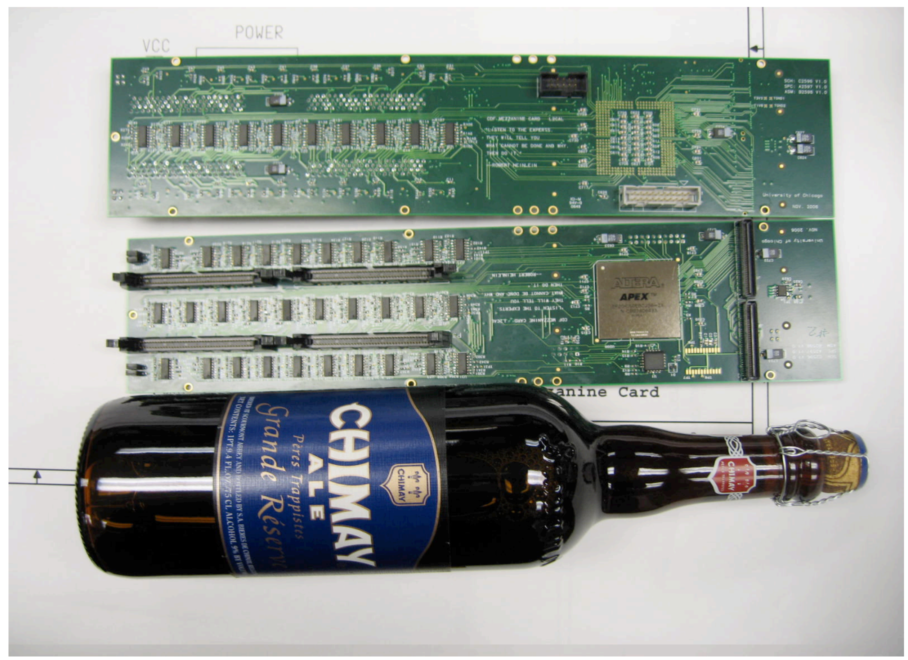


Calorimeter trigger upgrade

- Designed with $30 \times 10^{30} cm^{-2} s^{-1}$ in mind !
- Performed well for a long time but starting to show its age as the instantaneous luminosity moved toward $300 \times 10^{30} cm^{-2} s^{-1}$

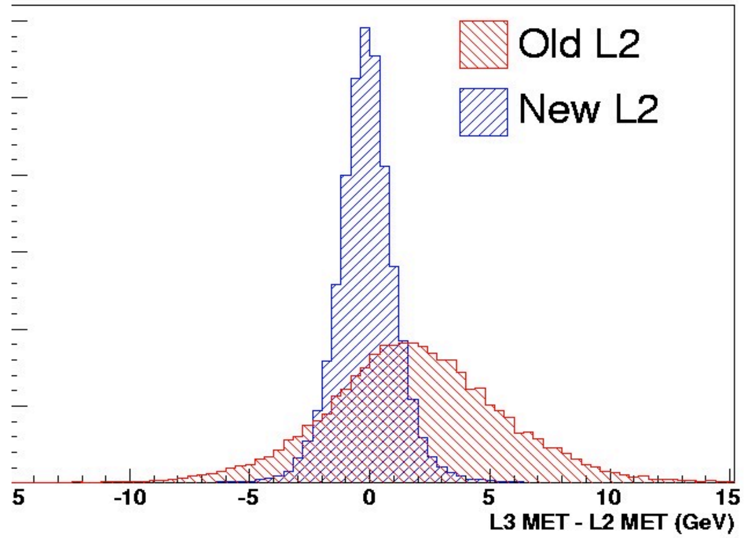
- Trigger upgrade is a major undertaking → starting in 2007 & Run II could end 2009 !

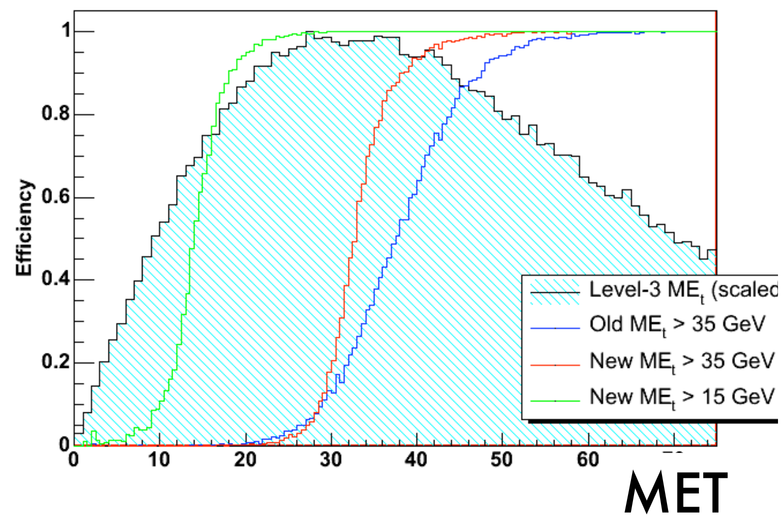
- Needed to design, build and commission new hardware/software < 1yr
  - Deadlines were tight
  - Stakes were high



Calorimeter trigger upgrade

- Upgrade:
  - More sophisticated algorithms (more like physics reconstruction)
  - Better resolution
- Challenge to make a software system as fast as hardware
- Upgrade completed < 12months
- Commissioned with essentially no impact on data taking !





Got MET ?

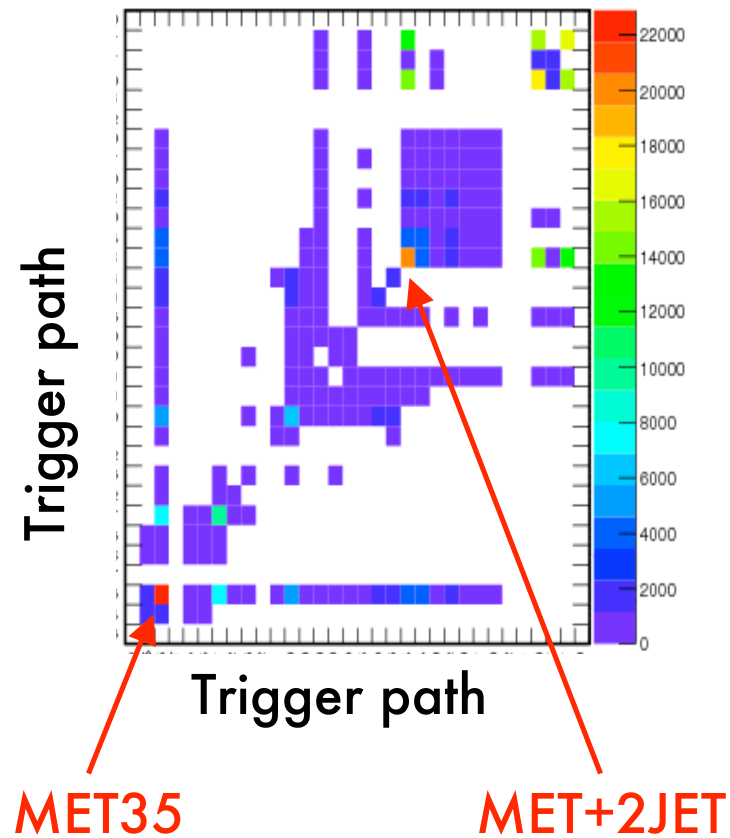
- Diboson production is a rare process
  → use all the data available

- Do not select on a particular trigger path

- If it has MET we take it
  - No data left behind policy

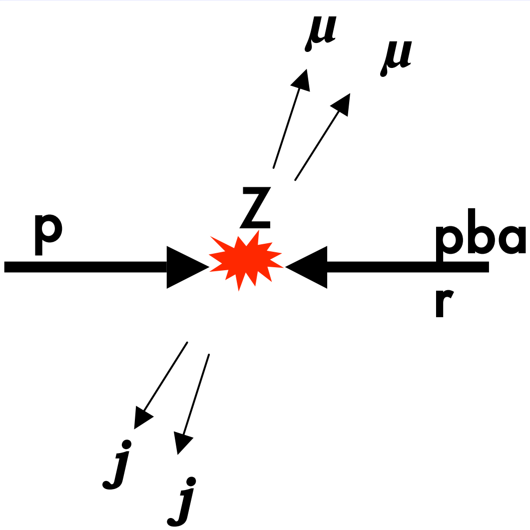
- Doing this does complicate the luminosity accounting
  - triggers changed over time, prescaled triggers etc

- If we had a standard candle to calibrate against that would be an enormous help



Z→μμ: a standard candle

- Calibrate the data sample against a well understood sample
  - Z→μμ mimics calorimeter MET



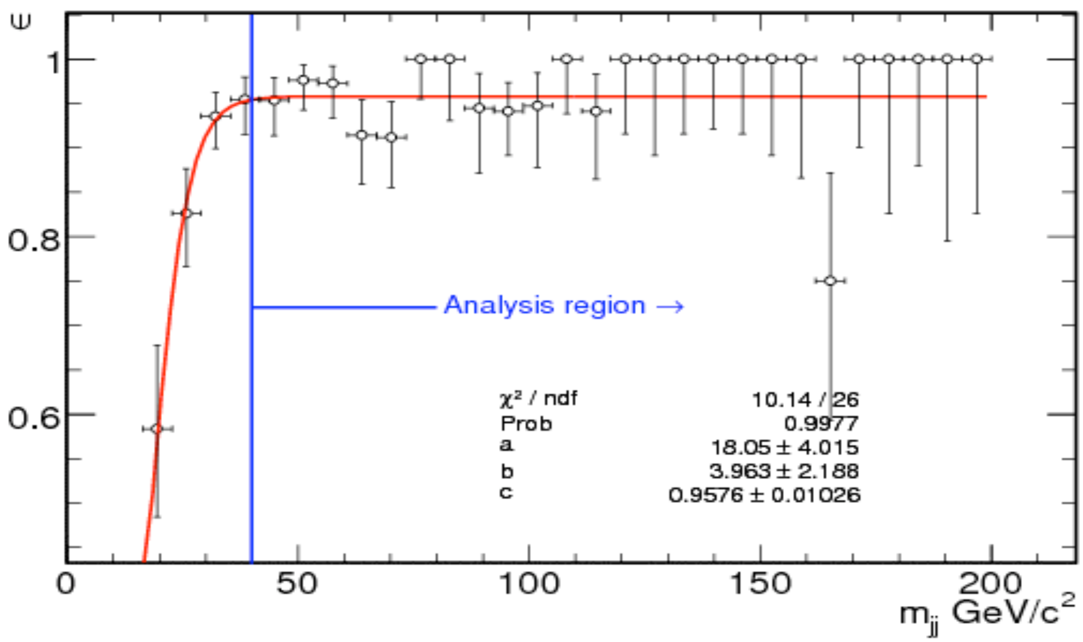
- Minimum ionizing particles
- Very little energy deposited in calorimeter

- Use Z→μμ to measure
  - -Trigger efficiency
  - -Luminosity

Trigger efficiency

Need trigger efficiency for the dataset → use standard candle

- Use $Z \rightarrow \mu\mu$ events from the high P_T muon trigger sample to find trigger efficiency
- The trigger turn on as a function of M_{jj} determines lowest M_{jj} to be used in the analysis (40 GeV/c^2)
  - Integrated efficiency of 96.4%±2.2%

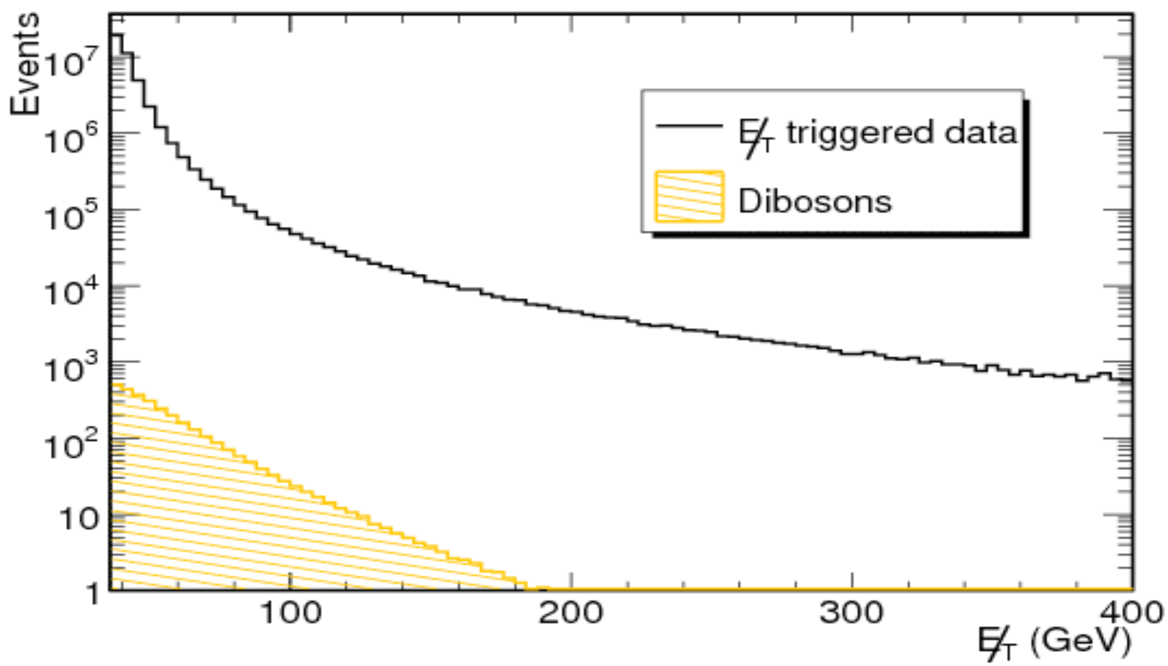


Challenges

Challenges of searching for dibosons in the MET+2jet signature:

- Technical/operational:
  - Need a lot of data ✓
  - High purity and high efficiency triggers at all luminosity ✓
- Analysis
  - Large background dominated by jet production and W/Z+jets
  - Extracting a small signal

Backgrounds to dibosons

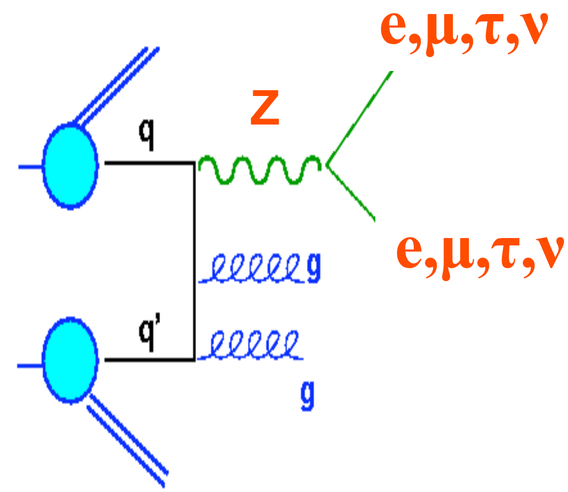


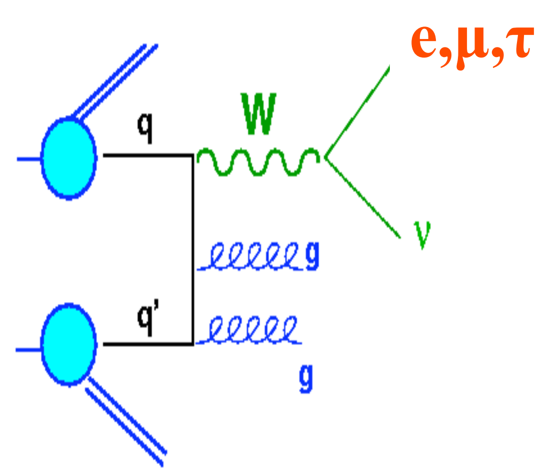
- Before selection cuts
  - Dibosons swamped by backgrounds !

Electroweak backgrounds

- Use Monte Carlo to describe background kinematics
- Z+jets
  - $Z \to ee$, $Z \to \mu\mu$, $Z \to \tau\tau$
  - $Z \to \nu\nu$ (this background looks like signal)
- W+jets
  - $W \to \mu\nu$
  - $W \to e\nu$
  - $W \to \tau\nu$

dominant ewk bkg

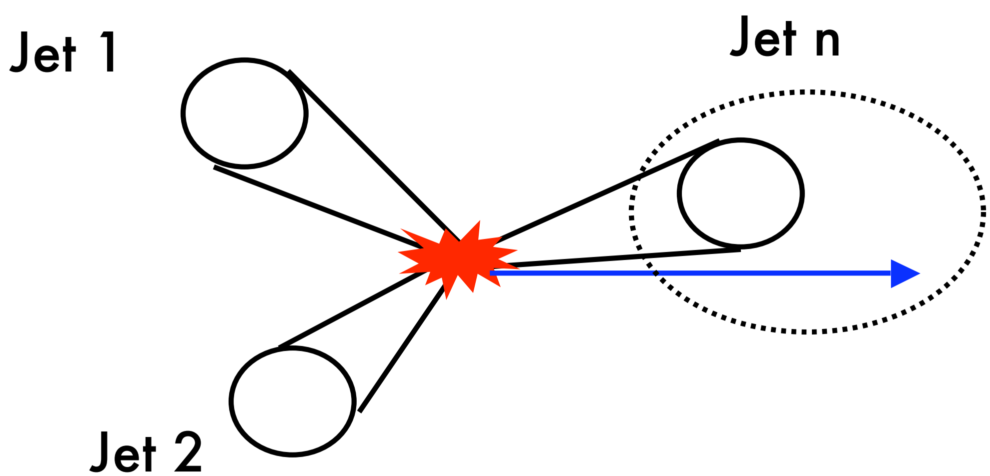




Multijet background

Jet production does not usually have large MET

- Can acquire MET from:
  - Mis-measurement of jets (fake MET) →Jet goes in cracks/un-instrumented region of the detector



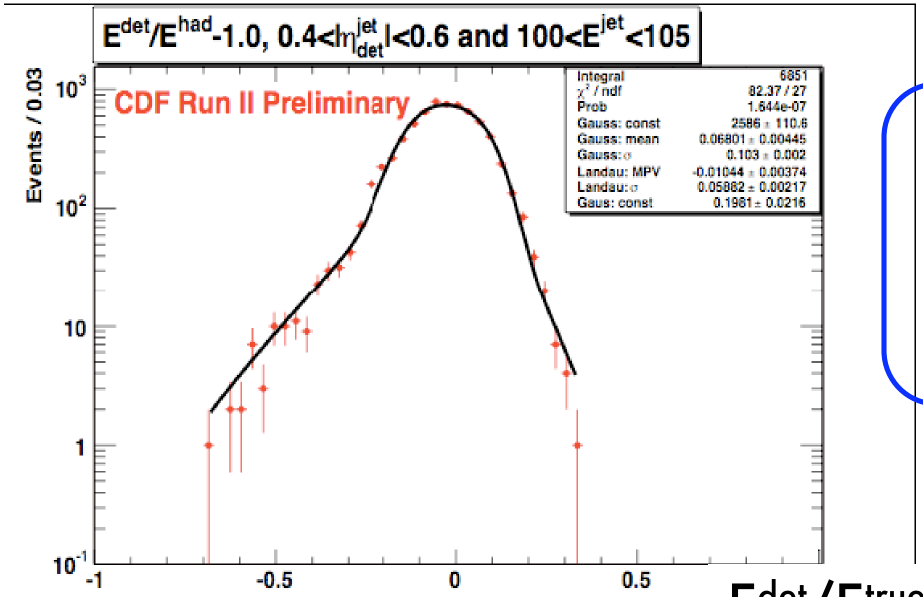
Mis-measured jet tends to align with MET
→Δφ should help rejection

- Our approach to fake MET:
  - Reject as much as possible
  - Use data to model whatever remains

MET resolution model

Mis-measurements in jet energy are leading source of fake MET

Example of jet energy resolution



$E^{det}/E^{true}-1$

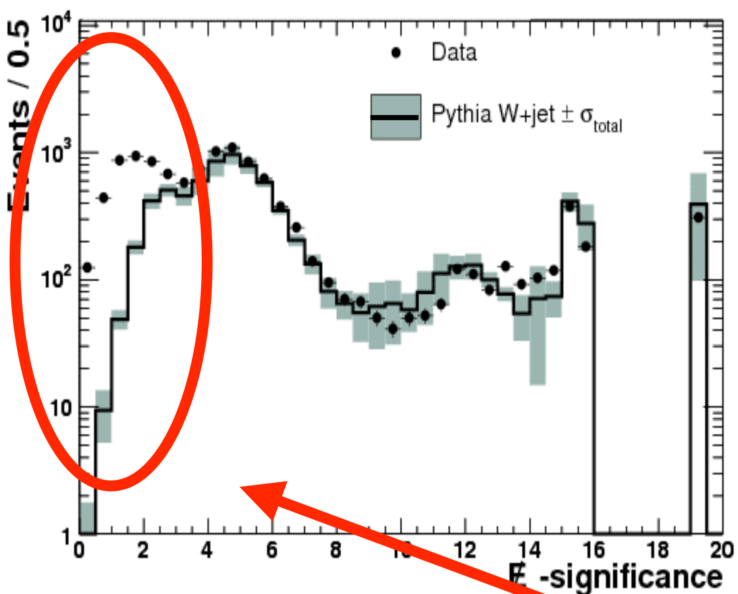
Find jet energy resolution as a function of E & η

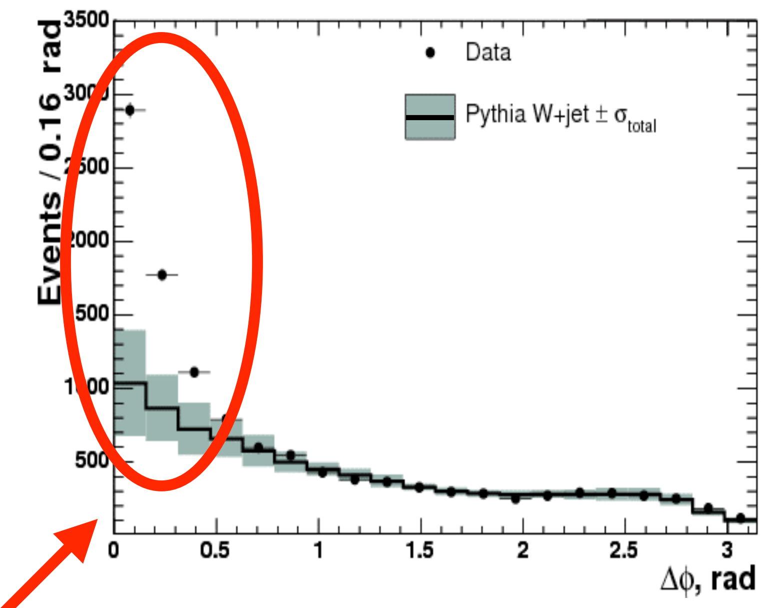
Select events with true MET

- Calculate MET-significance based on event configuration & known energy resolution
- Use significance to select true MET

MET model validation

- MET resolution validated in W+jets data





- Fake MET from jet background dominated regions
  - Low MET significance and MET aligns to a jet

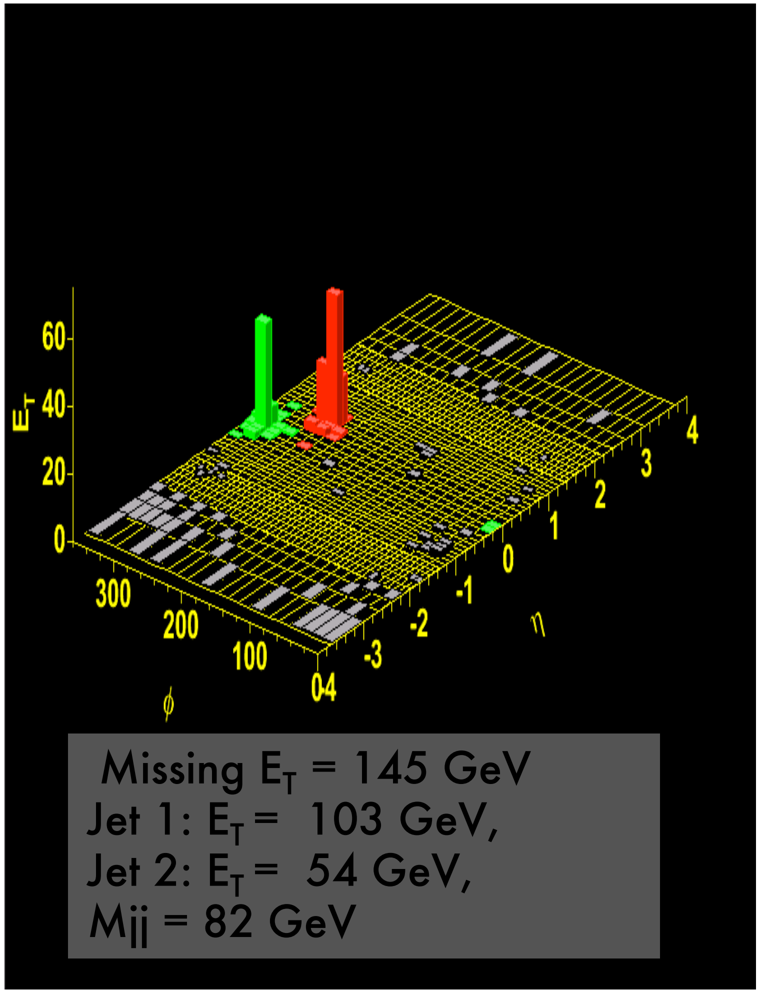
Diboson candidate selection

- Event selection:
  - MET > 60 GeV
  - 2 Jets, E_T > 25 GeV, $|\eta|$< 2.0
  - $\Delta\varphi$(closest) > 0.4
  - MET-significance > 4
  - E^{em}/E^{tot} 0.3-0.85
  - M_{jj} 40 GeV/c^2-160 GeV/c^2
  - Veto non collision background (non-collision backgrounds are out of time →calorimeter timing)
    - Remove non collision backgrounds to the 1% level

Jet background removal

- Remain sensitive to $\nu\nu jj$ & $l\nu jj$ by not having explicit lepton selection

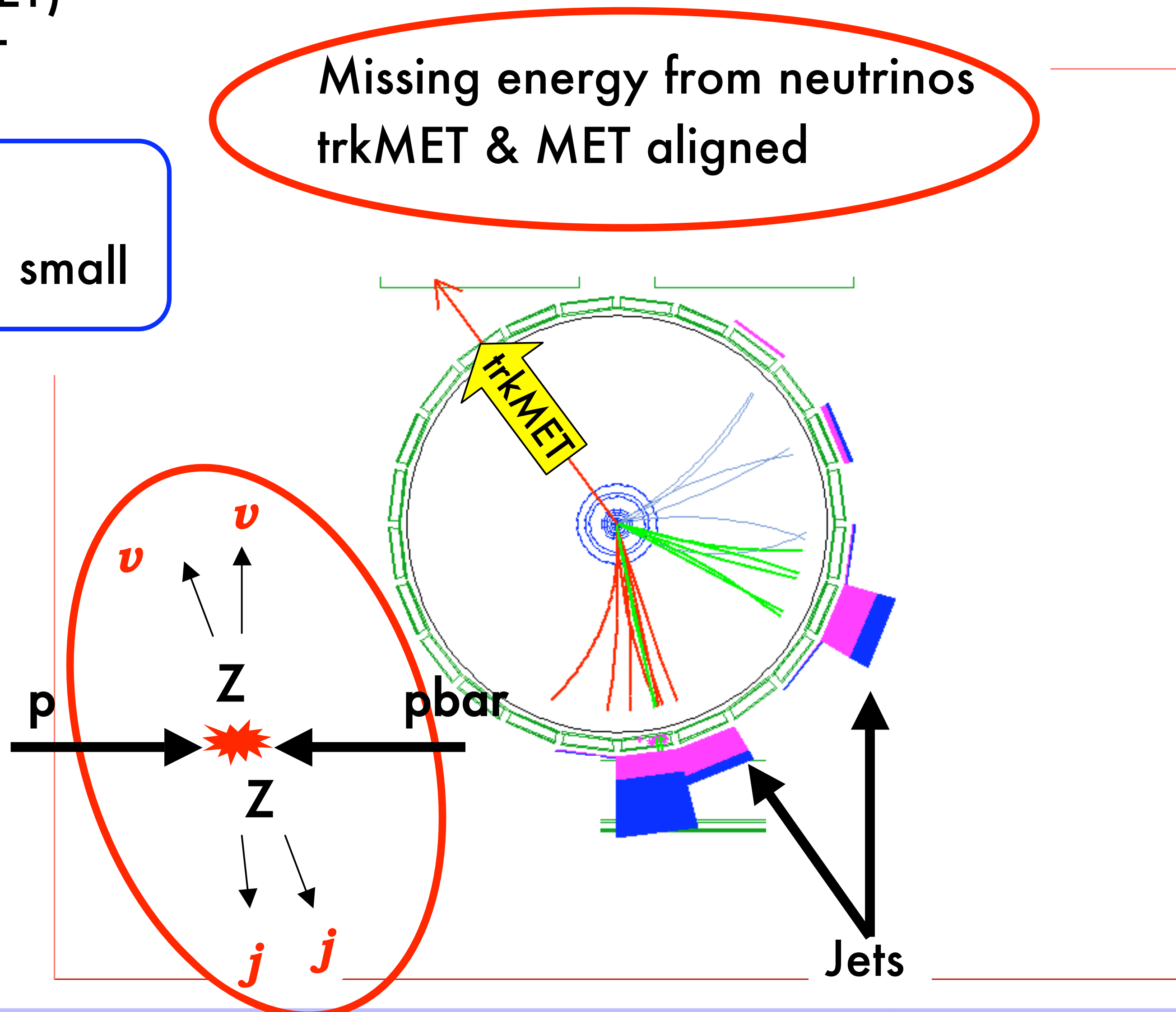
- 44910 events pass selection



Modeling the remaining jet background

- Track MET (trkMET) analagous to MET

- True MET
→Δφ(trkMET,MET) small

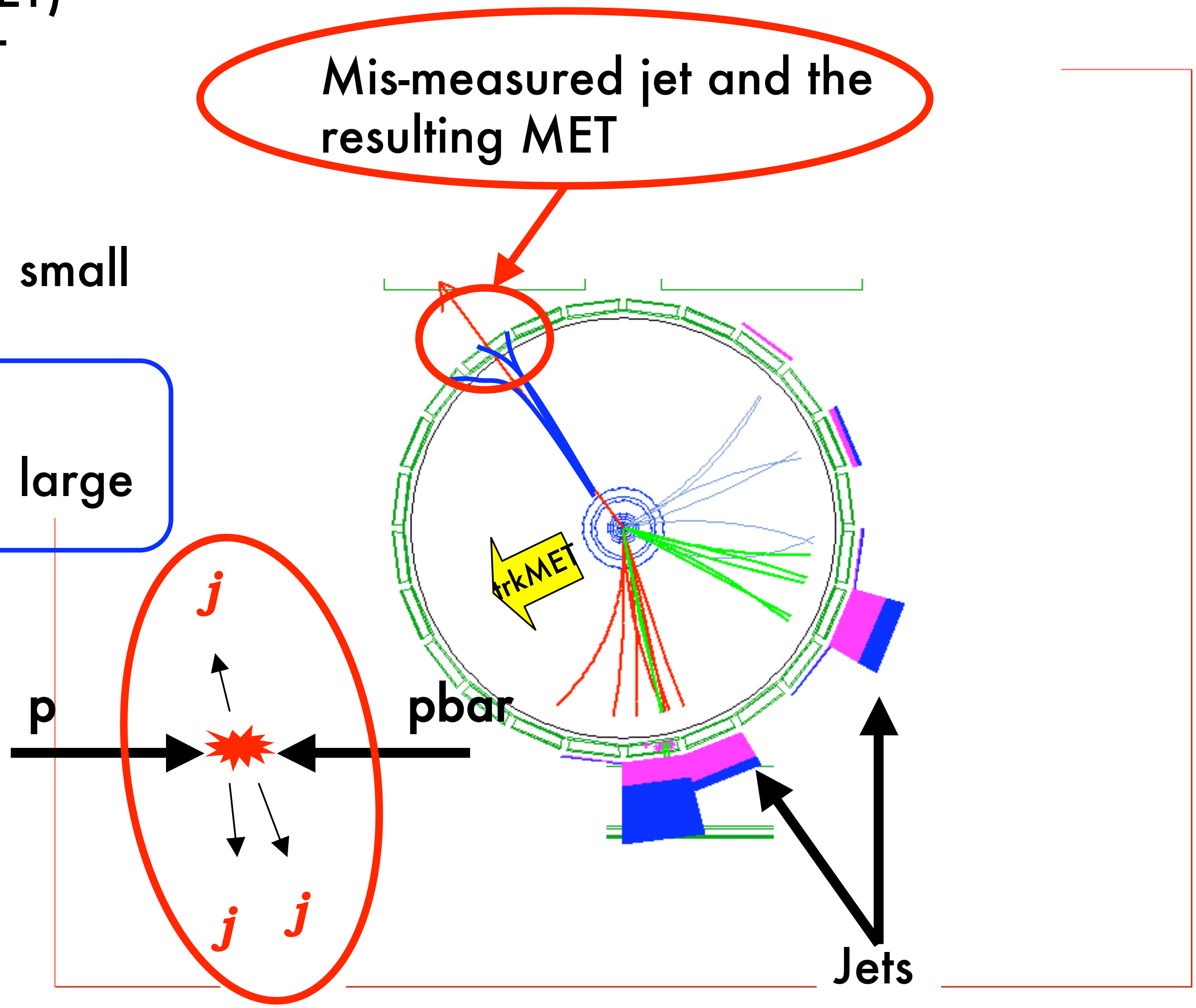


Modeling the remaining jet background

- Track MET (trkMET) analogous to MET

- True MET
→Δφ(trkMET,MET) small

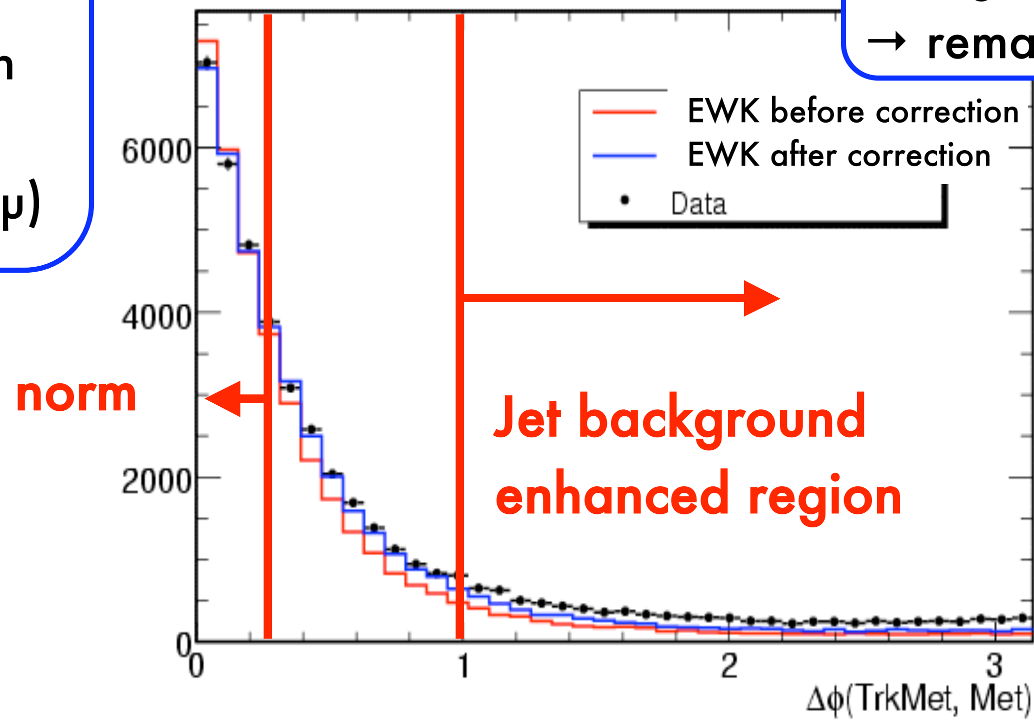
- Fake MET
→Δφ(trkMET,MET) large



Modeling the remaining jet background

Address resolution and modeling effects between data and MC with (Z→μμ)

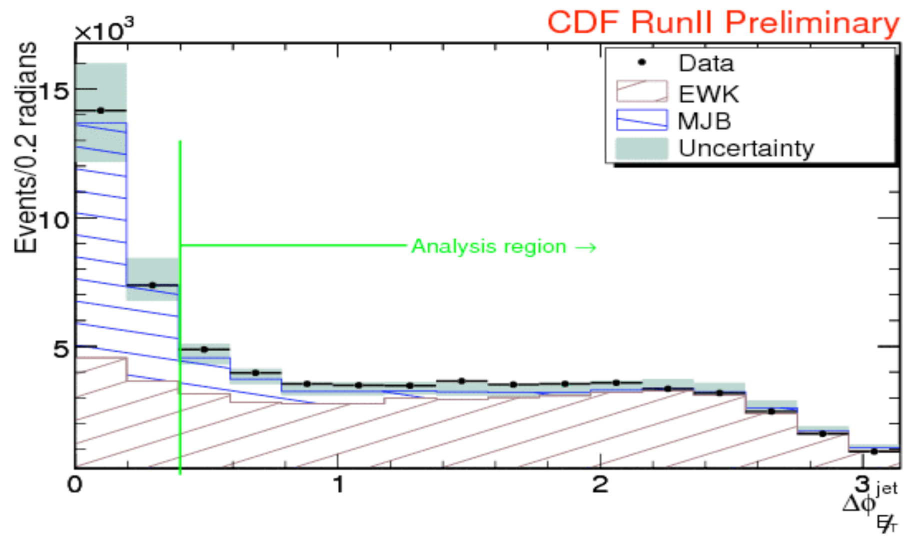
subtract electroweak background from the data → remaining jet background

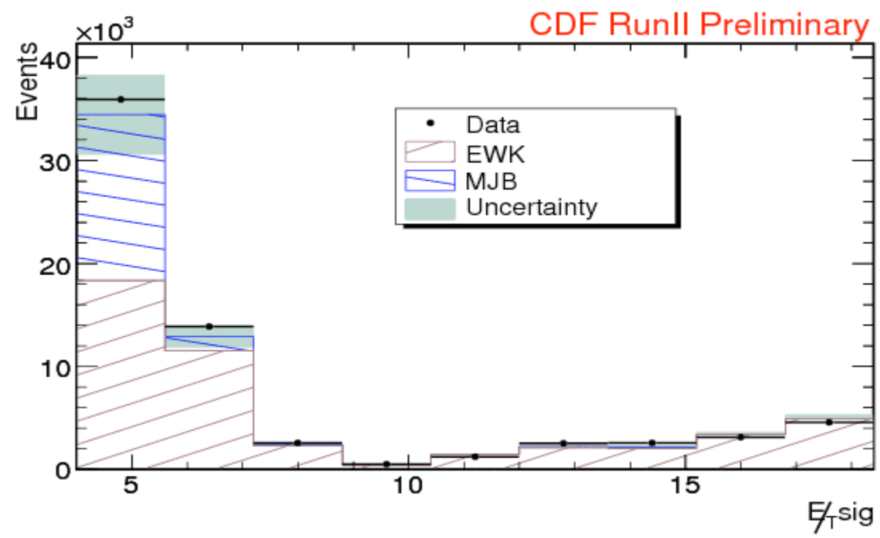


Account for jet background contribution in peak with dijet Monte Carlo

Checking the jet background model

- Check distributions that are sensitive to jet background
  - Δφ(closest)
  - MET-significance
- Electroweak background and the signal have the same shape in these variables
  - Combined into electroweak





Challenges

Challenges of searching for dibosons in the MET+2jet signature:

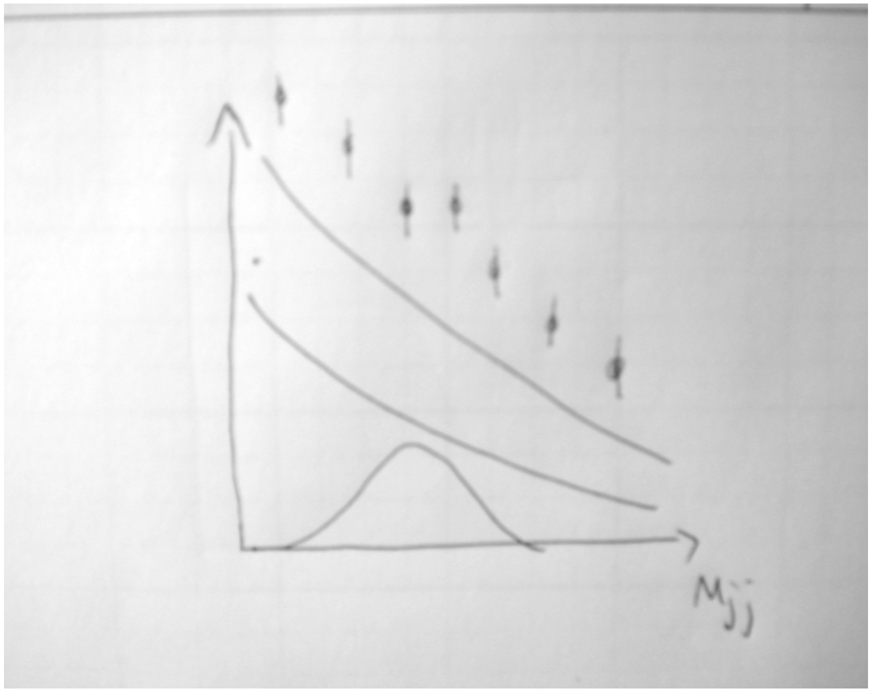
- Technical/operational:
  - Need a lot of data ✓
  - High purity and high efficiency triggers at all luminosities ✓
- Analysis
  - Large background dominated by jet production and W/Z+jets ✓
  - Extracting a small signal

Extracting the diboson signal

- Fit M_{jj} using 3 templates
  - Electroweak background
  - Jet background
  - Signal

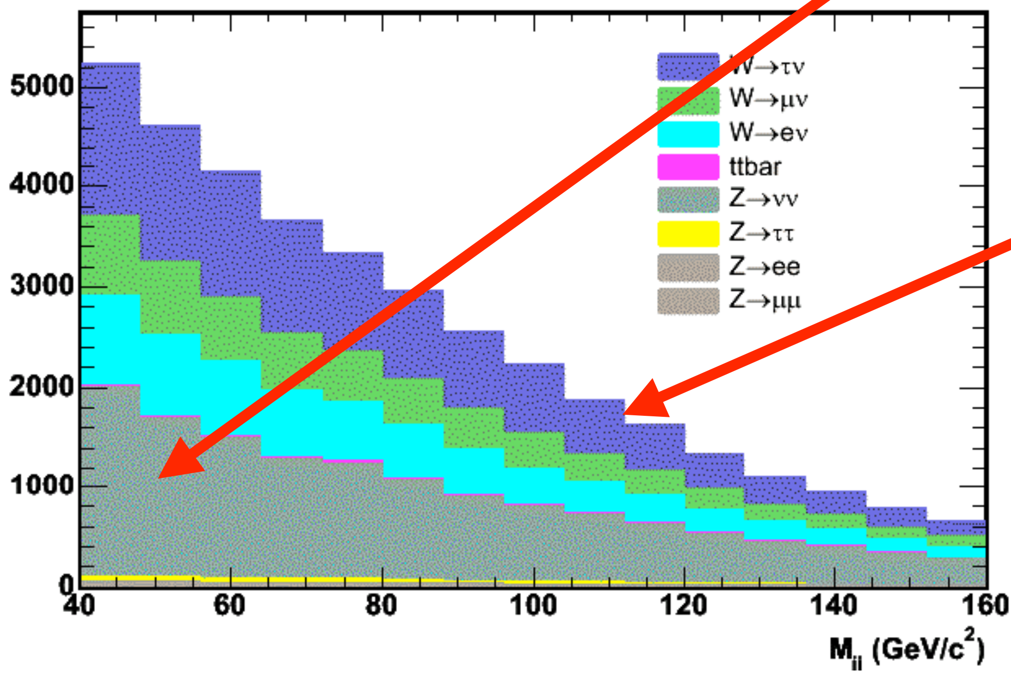
- Minimization of unbinned extended negative log likelihood

- Nuisance parameters in the fit
  - Jet energy scale (JES)
  - Jet background shape and normalisation



Templates (electroweak)

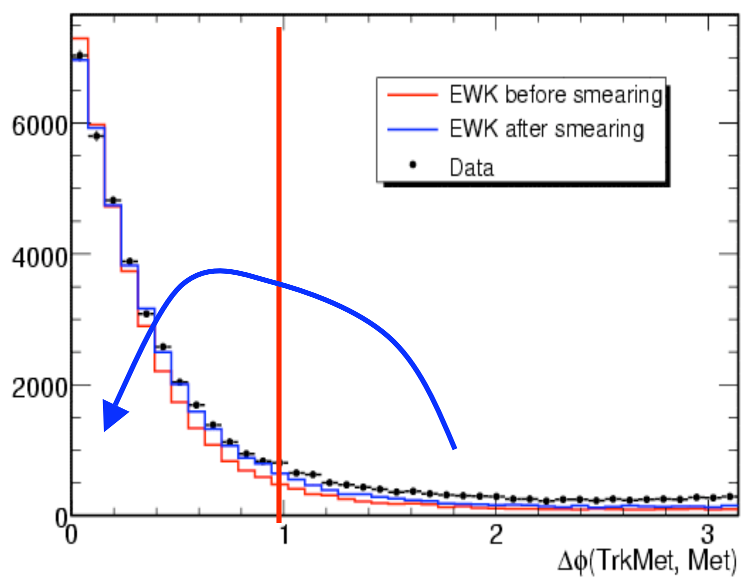
- The electroweak template is taken from MC
- Total number of electroweak events is unconstrained in the fit

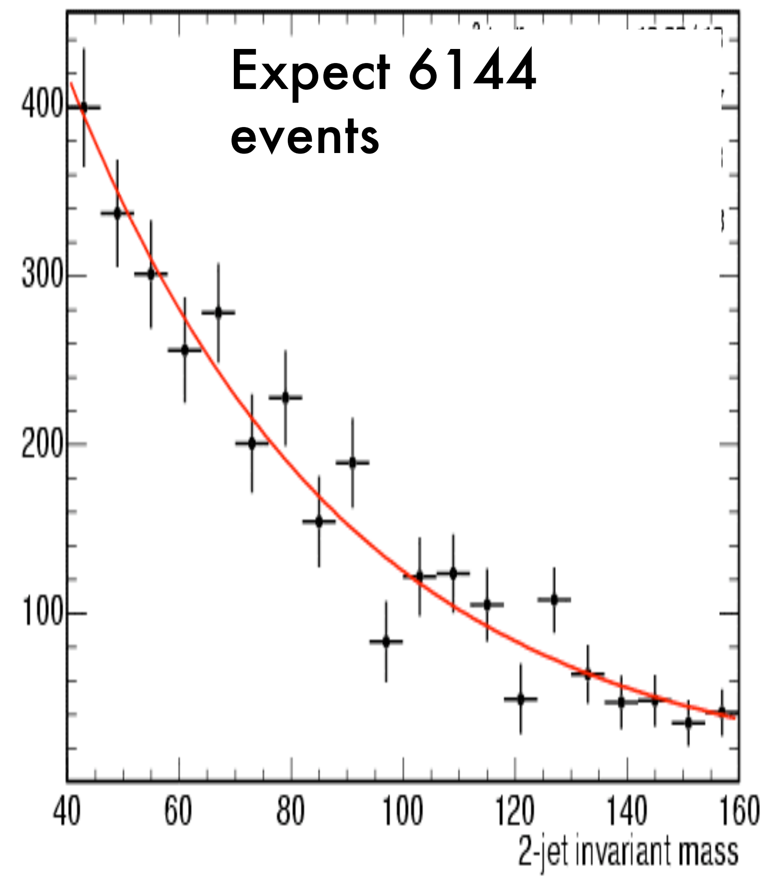


Sample	Exp # events	Exp % of sample
$Z \to \nu\nu$	12804	28.9
$Z \to ee$	5	0.0
$Z \to \mu\mu$	300	0.7
$Z \to \tau\tau$	430	1.0
$W \to e\nu$	6389	14.4
$W \to \mu\nu$	5672	12.8
$W \to \tau\nu$	10697	24.1
top	609	1.6
Total	31324	80.6

Templates (jet background)

- Shape & normalisation of jet background template comes from data-bkg with $\Delta\varphi$(trkMET,MET)>1.0
- Shape & normalisation are constrained





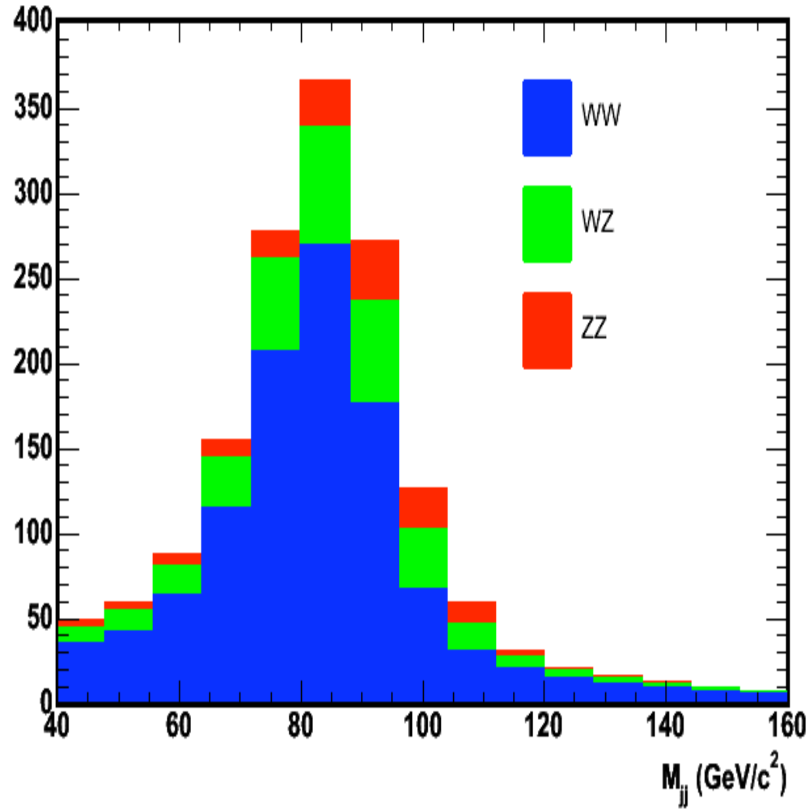
Uncertainty driven by extrapolation into the peak

Templates (signal)

- Due to dijet mass resolution we do not try to distinguish the individual signal components

Sample	Exp % of sample
Electroweak	80.6
Jets	15.8
Total bkg	96.4
Total Signal	3.6

- Expect 1398 signal events

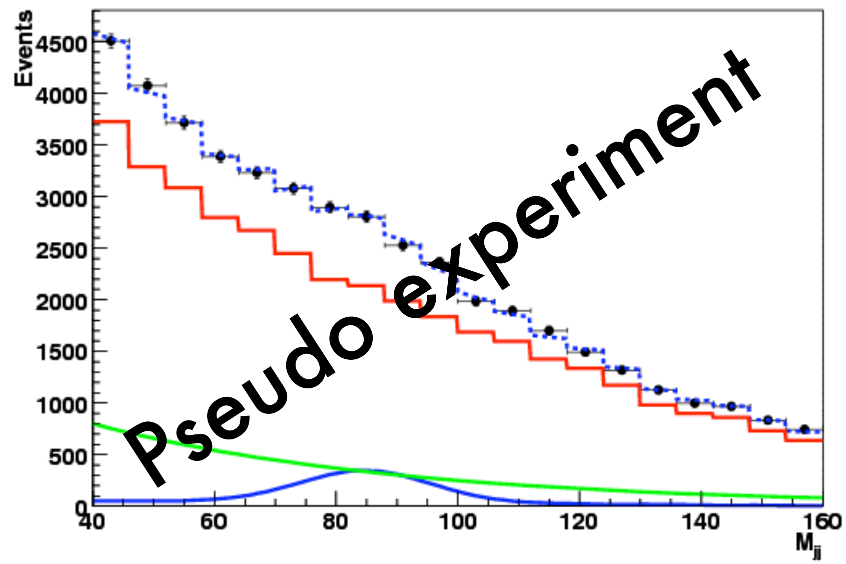


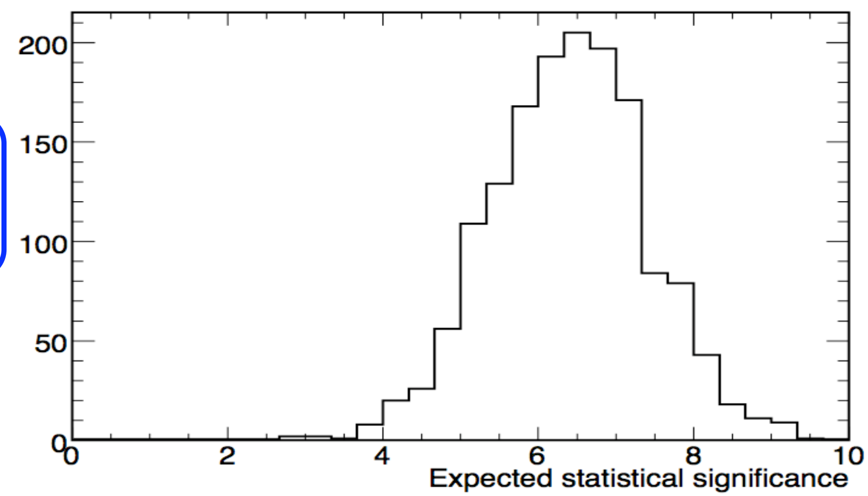
Expected significance

Pseudo experiments check

- PE's input from expectations
  - 1398 signal events
  - 31324 electroweak events
  - 6144 jet events

- Naively expected mean statistical significance ~ 6σ





Sources of systematics

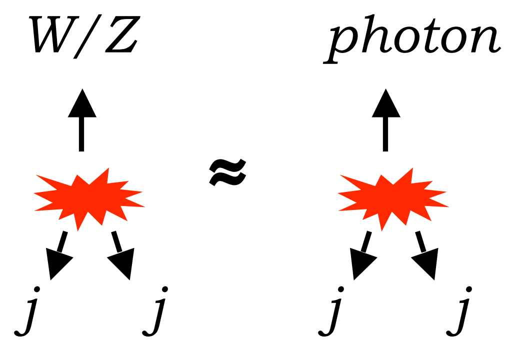
- Uncertainties associated with nuisance parameters folded into the statistical uncertainty of the fit
  - Jet background shape and normalisation
  - Jet energy scale

- Remaining sources of systematic uncertainty in the extraction:
  - Jet energy resolution
    - is treated by smearing the signal pdf by the resolution uncertainty
  - Electroweak template shape

How well do we know the electroweak background shape ?

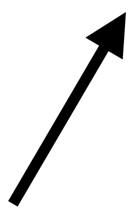
- Use photon+jet data to set the systematic uncertainty on the electroweak shape

- Basic idea:
  - Similar kinematics



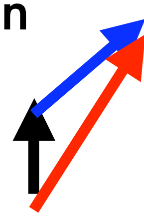
- Photon+jets events do not contain large MET

MET (MET+jets)



photon

MET



MET+photon = “MET”

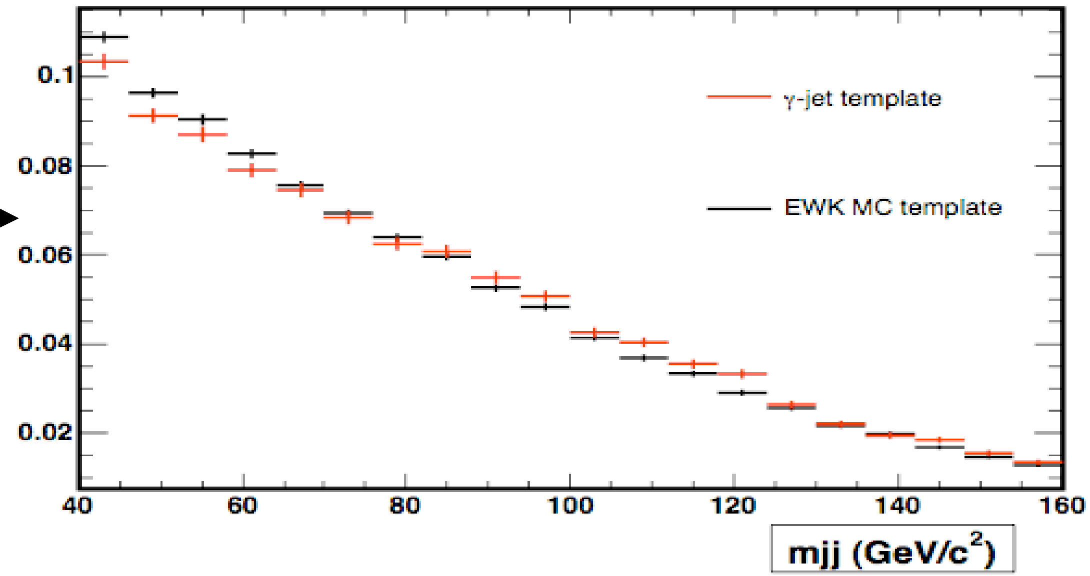
Electroweak background continued

Kinematics of photon+jets not identical to W/Z+jets→need to account for this:

- Method:

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

Data based alternative template→ systematic



Summary of Systematic Uncertainties

	% uncertainty	# signal events
EWK shape	7.7	117
Resolution	5.6	85
Total Extraction	9.5	144
	% uncertainty	# signal events
JES	8.0	121
JER	0.7	11
MET Model	1.0	15
Trigger efficiency	2.2	33
ISR/FSR	2.5	38
PDF	2.0	30
Total Acceptance	9.0	136
Lumi	6.0	91
Total Uncertainty	14.4	218

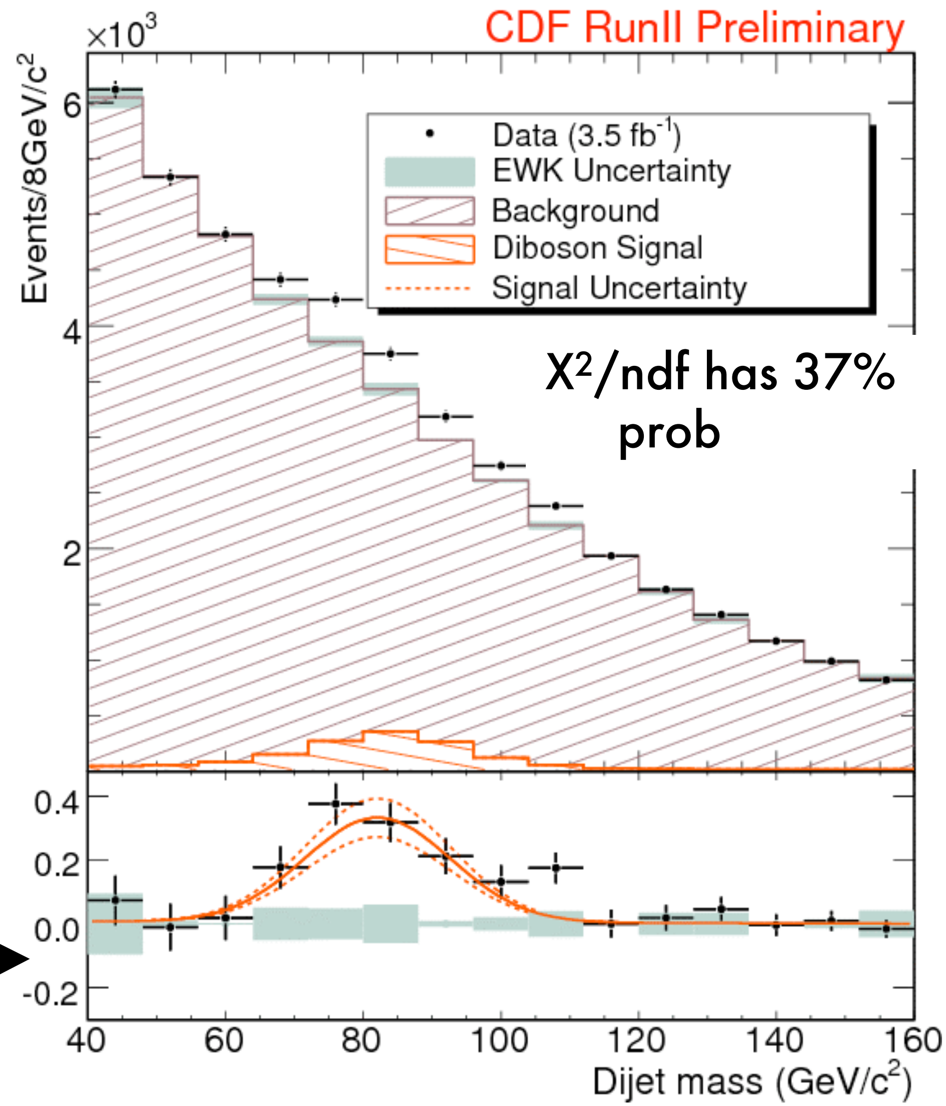
Uncertainty on extraction

Additional uncertainties that contribute to X-section

Signal extraction

- Fit result:
  - 1516 ±239 (stat) ± 144(sys)
  - Expected 1398 ± 243

Data-background



X^2/ndf has 37% prob

Significance

Quantifying the probability that the background could fluctuate up and mimic the fitted signal

- Naively $1516/\sqrt{(239^2+144^2)} = 5.4\ \sigma$

Expand on naïve estimation of significance

- Consider parameter variations for all sources of uncertainty
  - Compare likelihood of background only fit with the full fit result
  - Convert the differences into significance

- The lowest significance returned was 5.3σ

Cross section continued

$$\sigma = \frac{N(\text{extracted})}{A \times \varepsilon \times L}$$, A= acceptance, ε= efficiency, L = luminosity

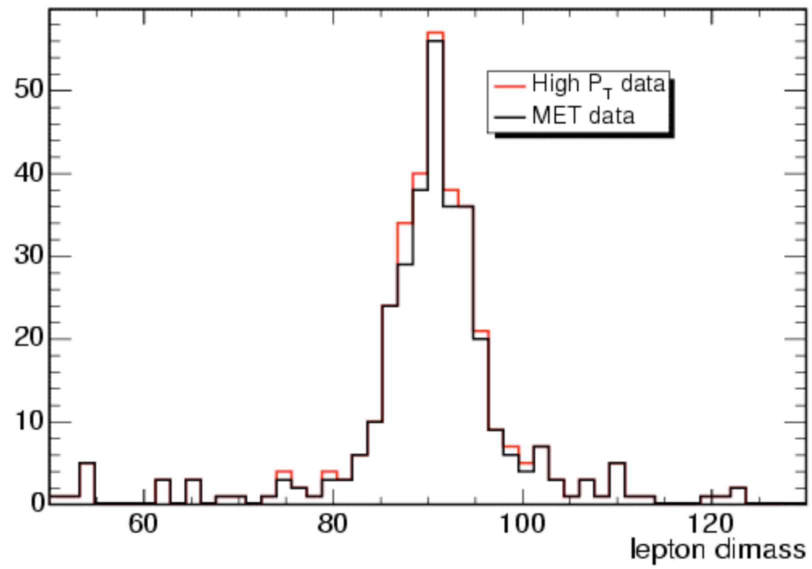
- Number of extracted events 1516
- Efficiency
  - Trigger 96 %
  - Cosmic 99 %
- Acceptance is weighted by WW, WZ, & ZZ xsec

Process	X-sec (pb)	Acceptance (%)
WW	11.7	2.5
WZ	3.6	2.6
ZZ	1.5	2.9

- Luminosity ?

Luminosity calibration

- Measure luminosity based on our standard candle
- Rerun analysis→ high P_T muon data & MET data
  - Select $Z \rightarrow \mu\mu$ events and compare number of events in the two samples



$$L_{MET} = \frac{N_{MET} \cdot L_{muon}}{N_{muon} \cdot \varepsilon_{MET}}$$

Measured cross section: 18.0±2.8(stat) ±2.4(sys) ± 1.1(lum) pb

Conclusions

- First observation of vector boson pairs with hadrons at the Tevatron
- Measured the diboson production cross section
  - Measured cross section:

Now for the Higgs

    18.0±2.8(stat) ±2.4(sys) ± 1.1(lum) pb
  - SM cross section:

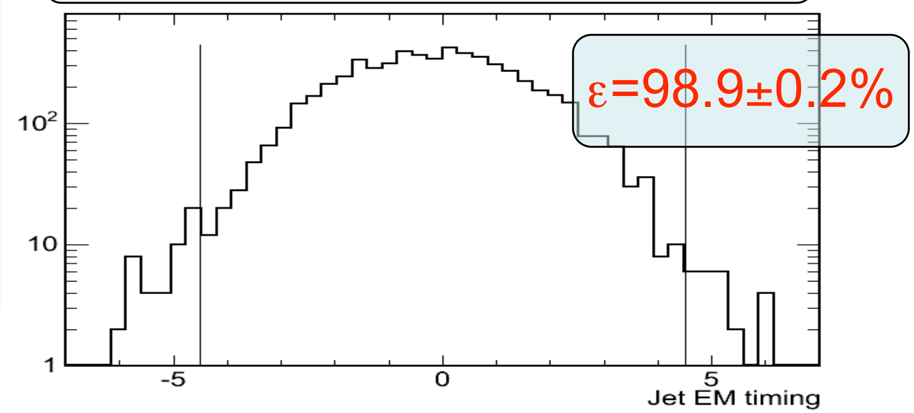
    16.8±0.5 pb

Back up slides

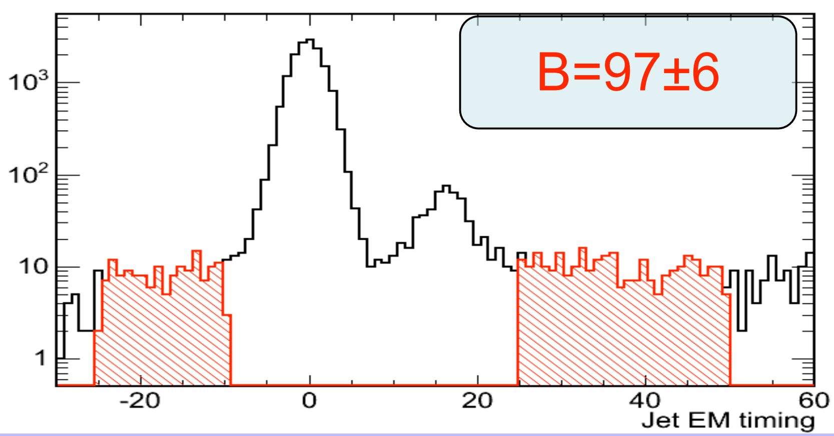
Cosmic removal

- 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

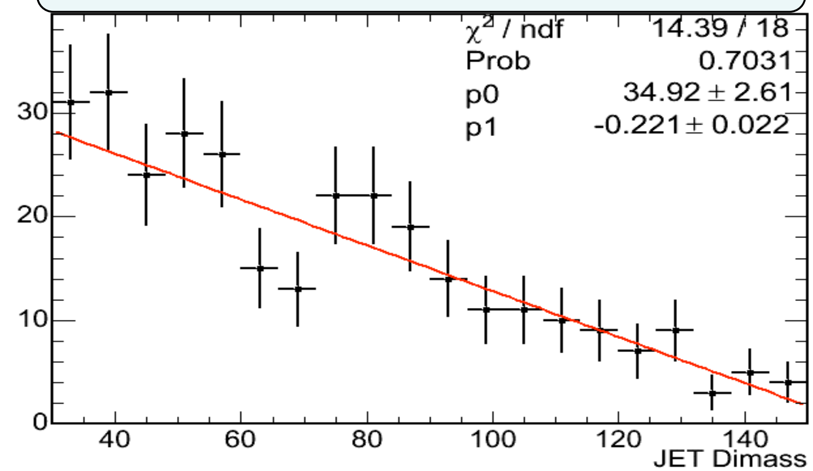
Z→ll to measure efficiency



Data to estimate bckg.



Similar to EWK

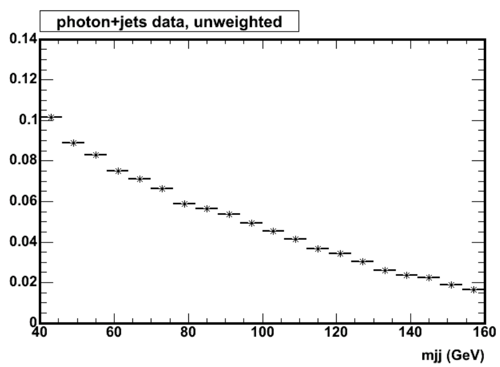


QCD background

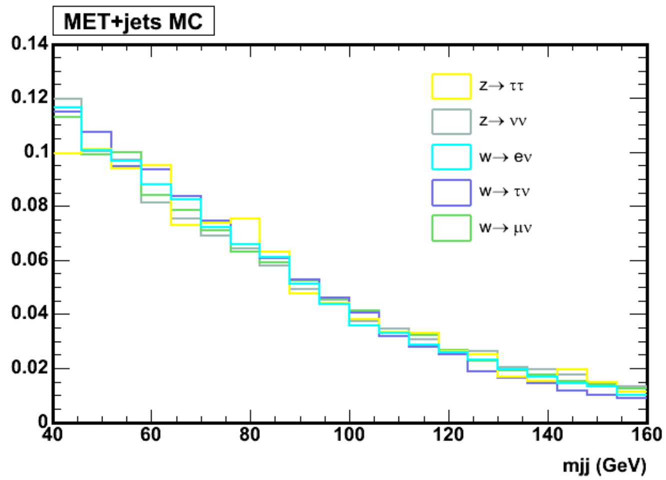
- Track met:
  - vector sum of tracks: calculate track met and track met φ and use a 0.5GeV track threshold)
- Compare track met φ with cal met φ
  - expect alignment when there is no calor mis-measurement.
- Use aligned region (peak) to normalise
- Use the region where track met and calor met are not aligned to construct the Mjj distribution for QCD.
- Calibrate with $Z \rightarrow \mu\mu$ sample

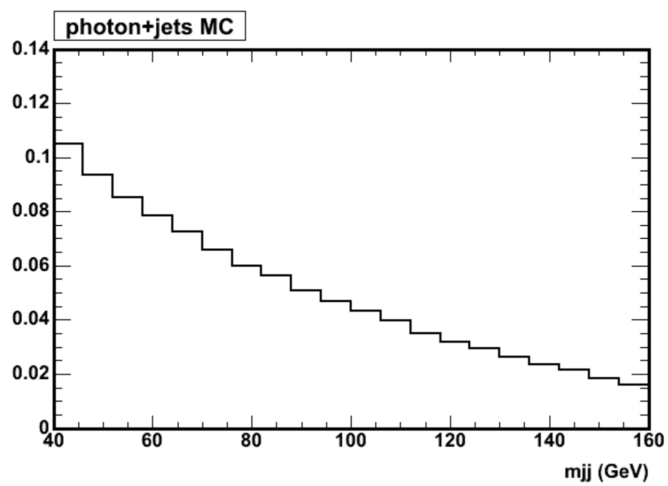
Re-weighting photon+jets

- 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

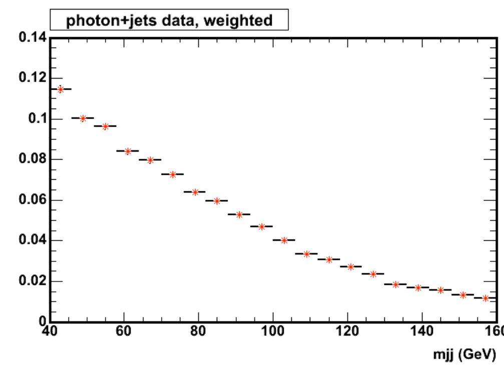


X





=



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

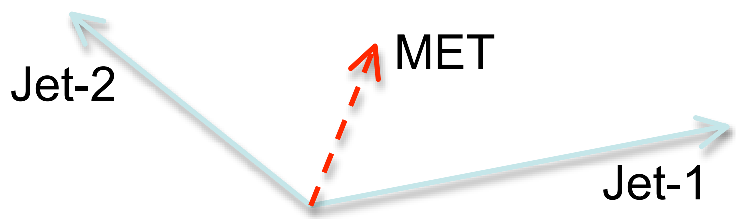
Fit results

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

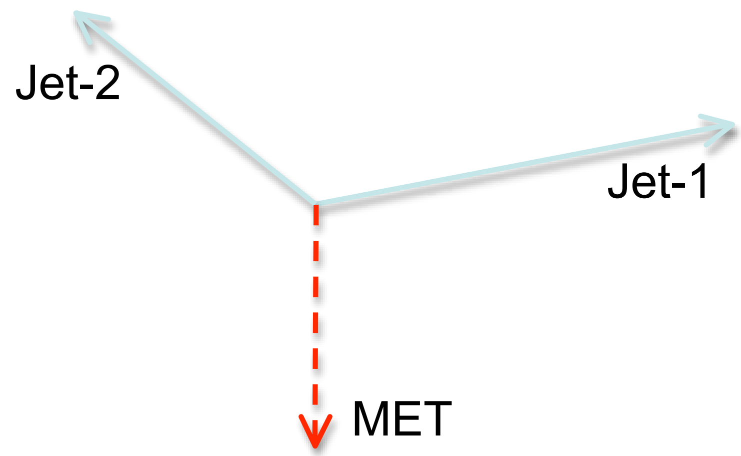
- Jet bkg background template (6144 events in peak and out , slope -0.02)
  - Jet slope ~20% uncertainty
  - Jet norm ~20% uncertainty
  - (0.724x-0.02) is the fit result

Explanation of "signed" metsig

Processes with real MET usually don't have this configuration:
negative metsig



Typical configuration for processes with real MET:
positive metsig



Significance

- Fix parameters, the float one at a time (always floating sig)
- Conservative approach if one assumes syst are uncorrelated
- Compare default fit with background only fit (in above scheme)