Milestone for Tevatron Higgs Searches:
First Observation of Diboson Production in Hadronic Final States

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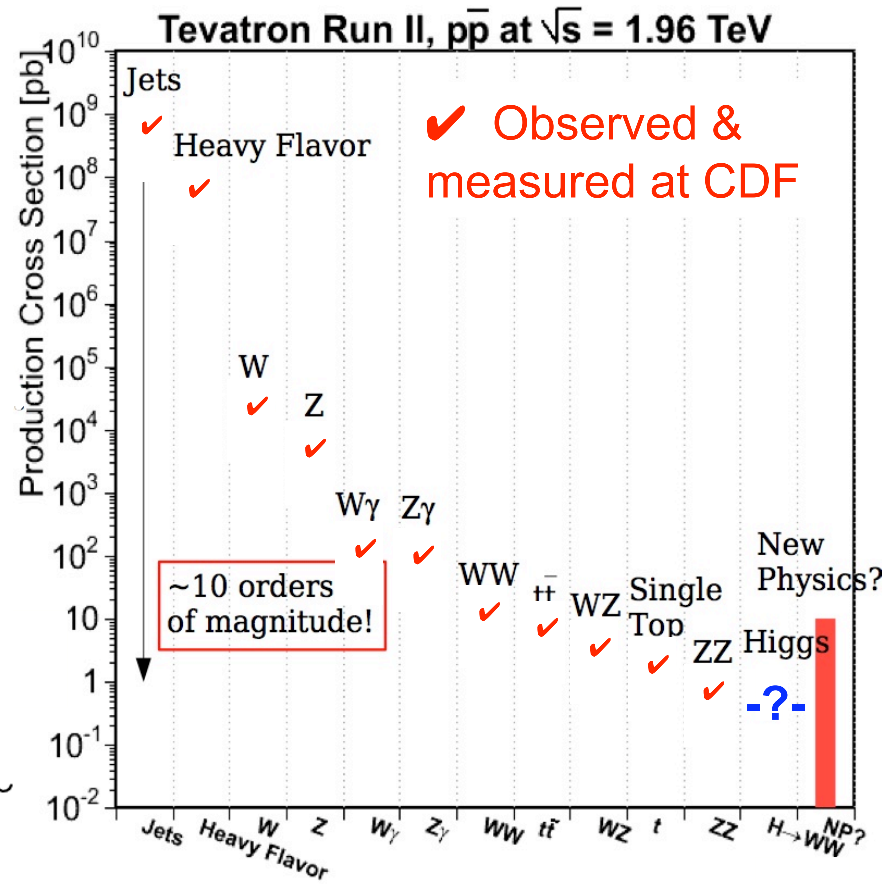
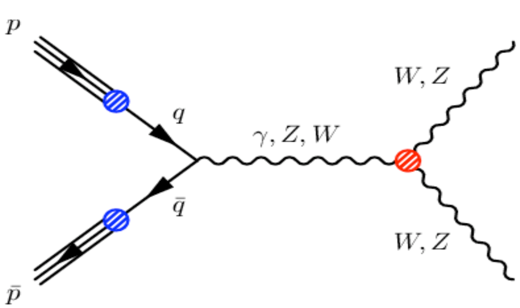
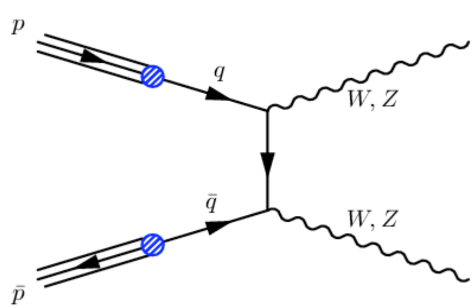
Diboson Processes at the Tevatron

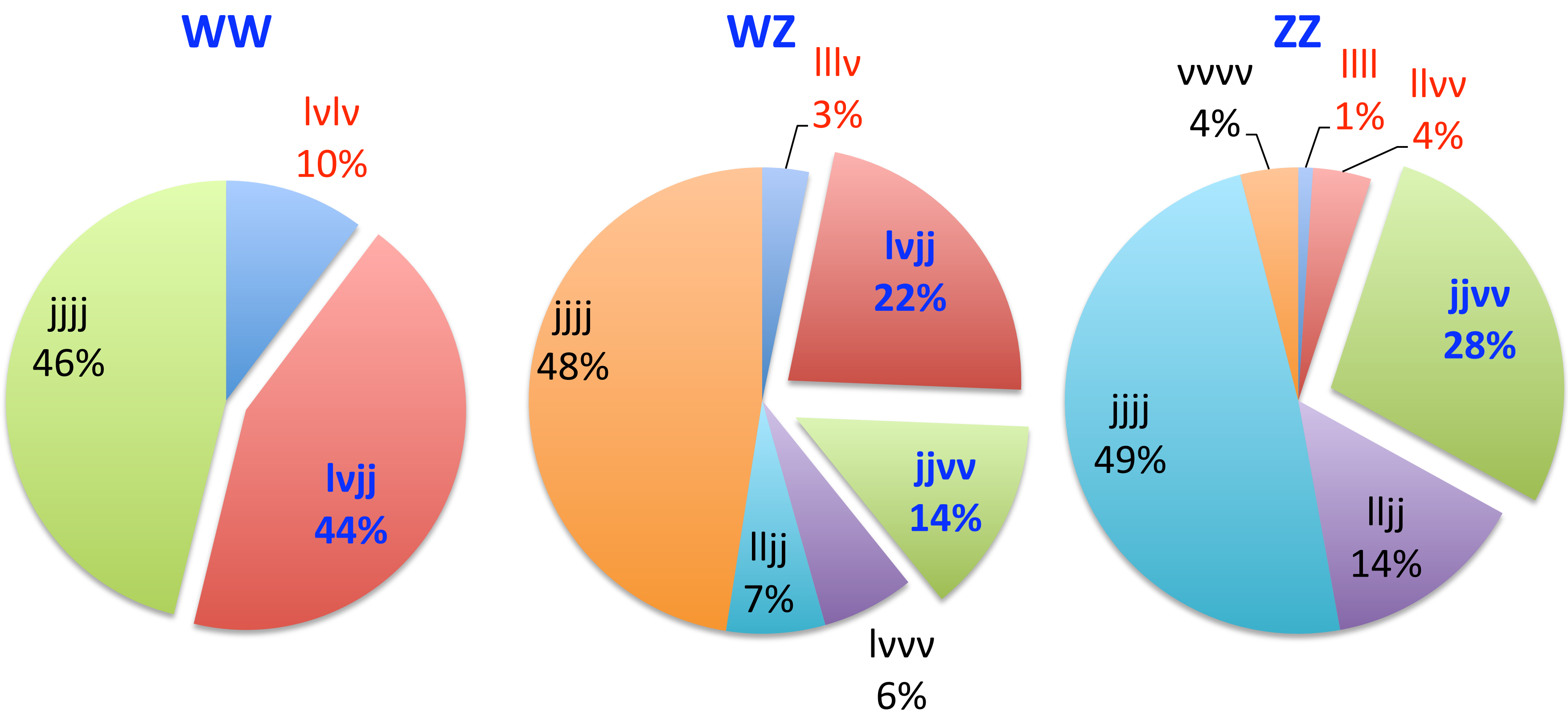
- $SU(2)_L \otimes U(1)_Y$
  - electroweak (EW) group structure is central to Standard Model
- EW boson self-interactions are completely dictated by gauge symmetry
  - Sensitive to new physics







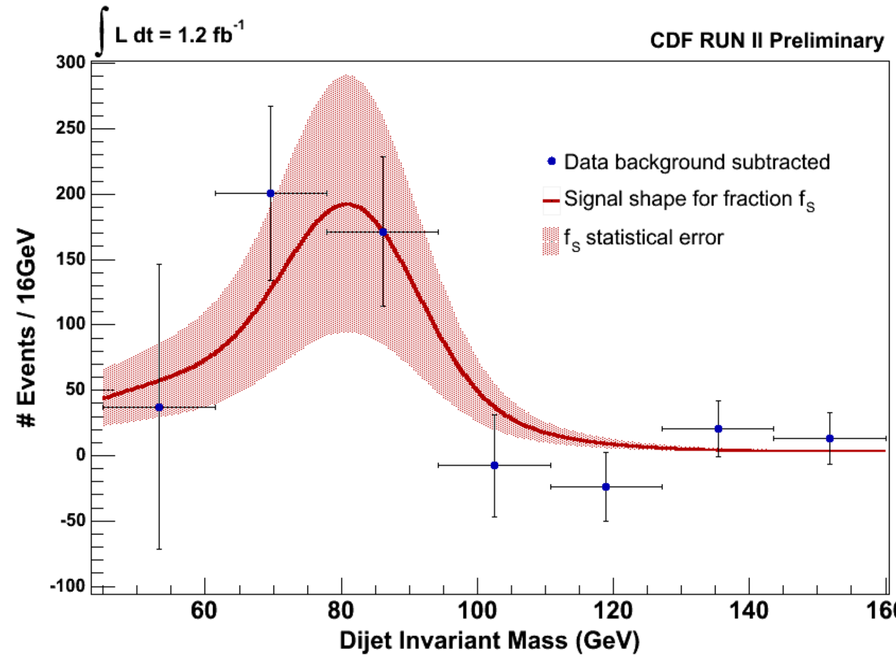
Diboson Final States

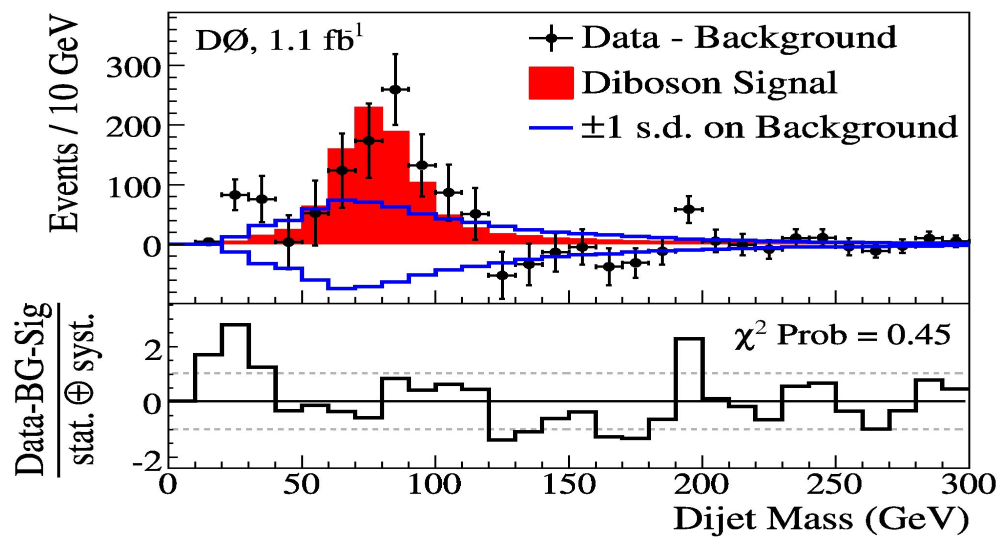


- Dibosons were discovered in lνlν, lllν, llll, and llνν, modes
  - Small branching ratios, clean signatures, easy to trigger
- "Semileptonic" modes with at least one W/Z→jj
  - ~40% branching fractions, ~1000× backgrounds, difficult to trigger

Recent Tevatron Results with Dibosons

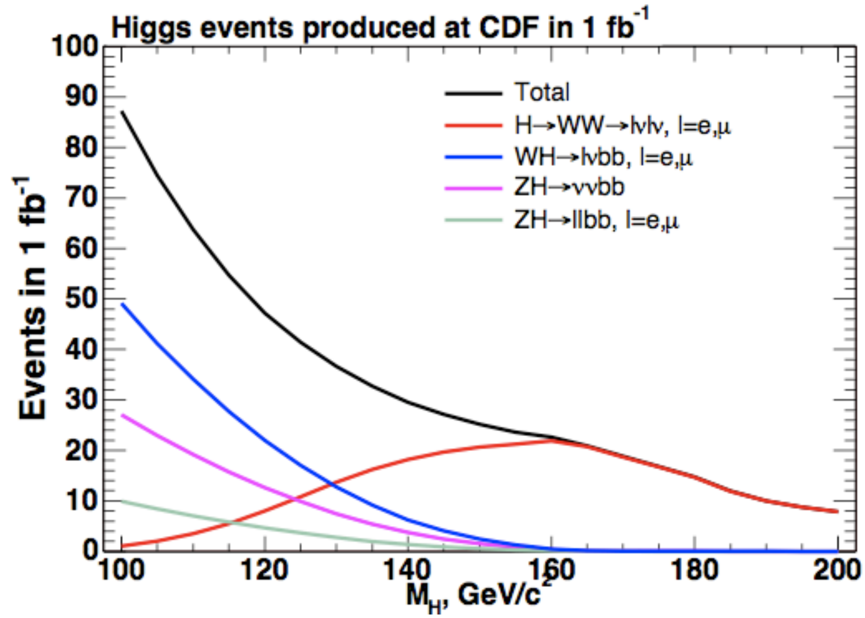
- Dibosons (WW, WZ, and ZZ) were observed in fully leptonic mode
- Dibosons at Tevatron were not previously observed in lνjj or ννjj modes
  - CDF: 2.4σ in WZ/WW→lνjj
  - D0: 4.3σ in WZ/WW→lνjj
    - evidence

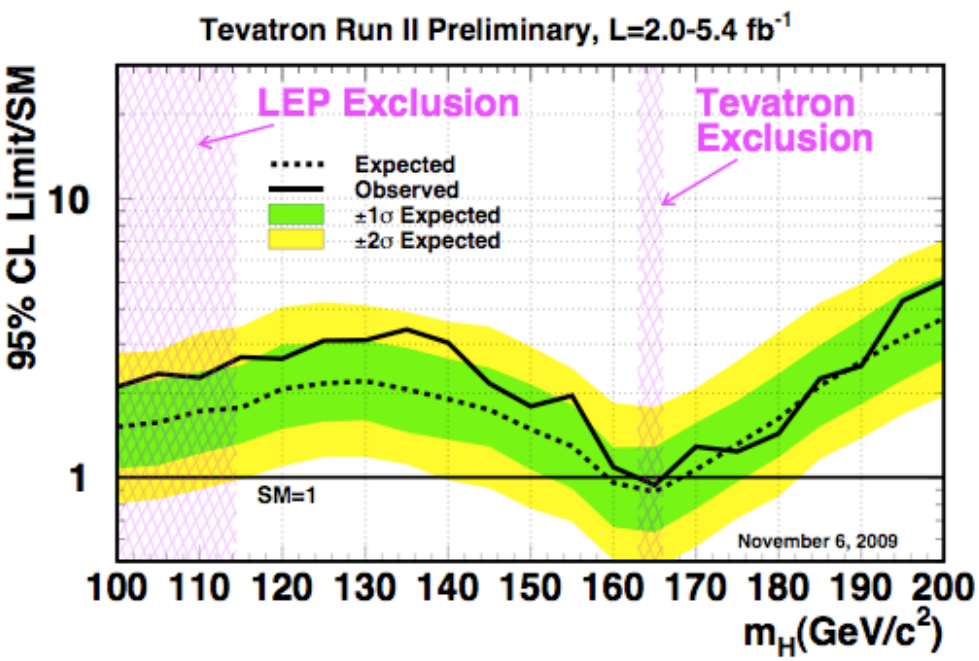


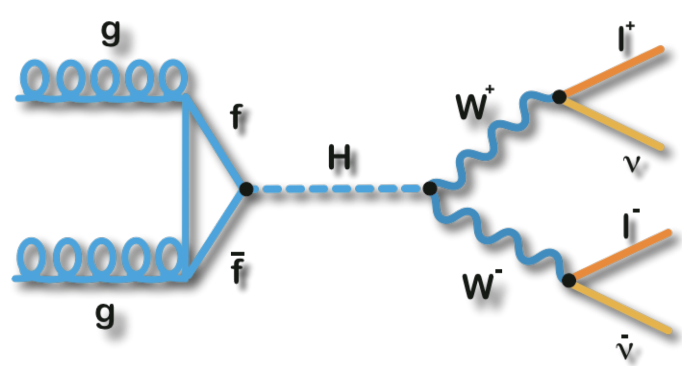


From Dibosons to Higgs Searches

- **$H \to WW$** is dominant decay channel for $M_H > 135$ GeV/c^2
  - Direct WW production is largest non-reducible background
    - Need to be well measured and understood

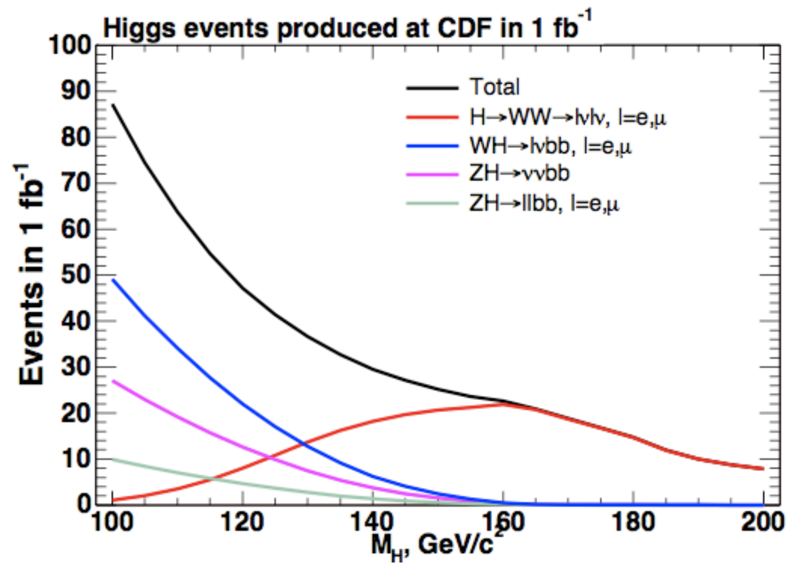


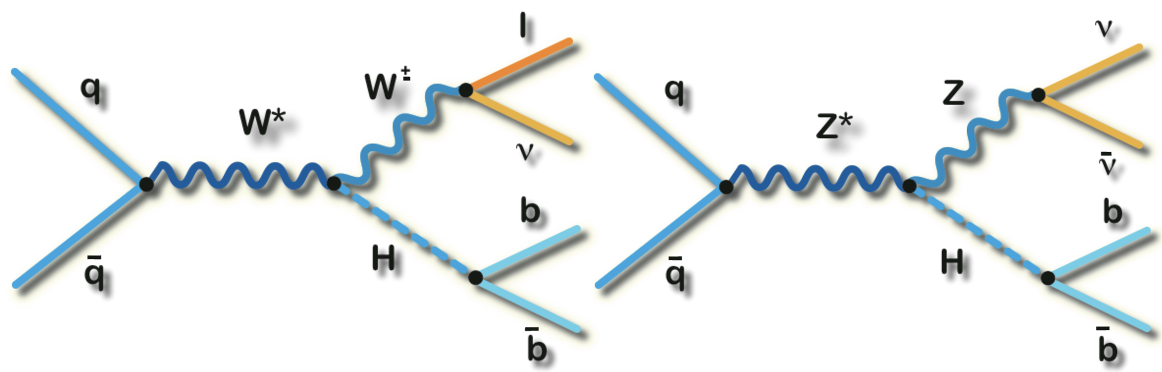




From Dibosons to Higgs Searches

- **HW→νl+bb** and **HZ→νν+bb** are leading channels for light Higgs (M_H<135 GeV/c^2) searches at the Tevatron
  - Similar signatures and challenges to **WW/WZ→νl+jj** and **ZZ/WZ→νν+jj**
    - Small signal in a large background
    - Test of analysis techniques

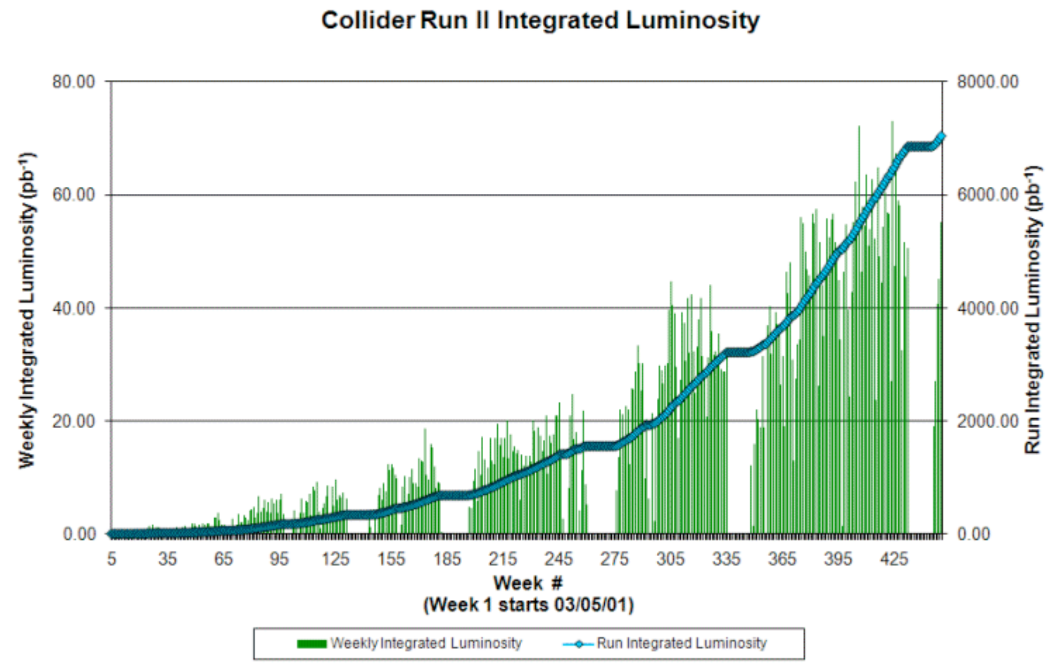




- Recent CDF Higgs results for M_H=115 GeV/c^2
  - Observed limit
    - HW: 5.3×σ_{SM} in 4.3 fb^{-1}
    - HZ: 6.1×σ_{SM} in 3.6 fb^{-1}

Road to Higgs is paved with Dibosons

Tevatron is Running Very Well!

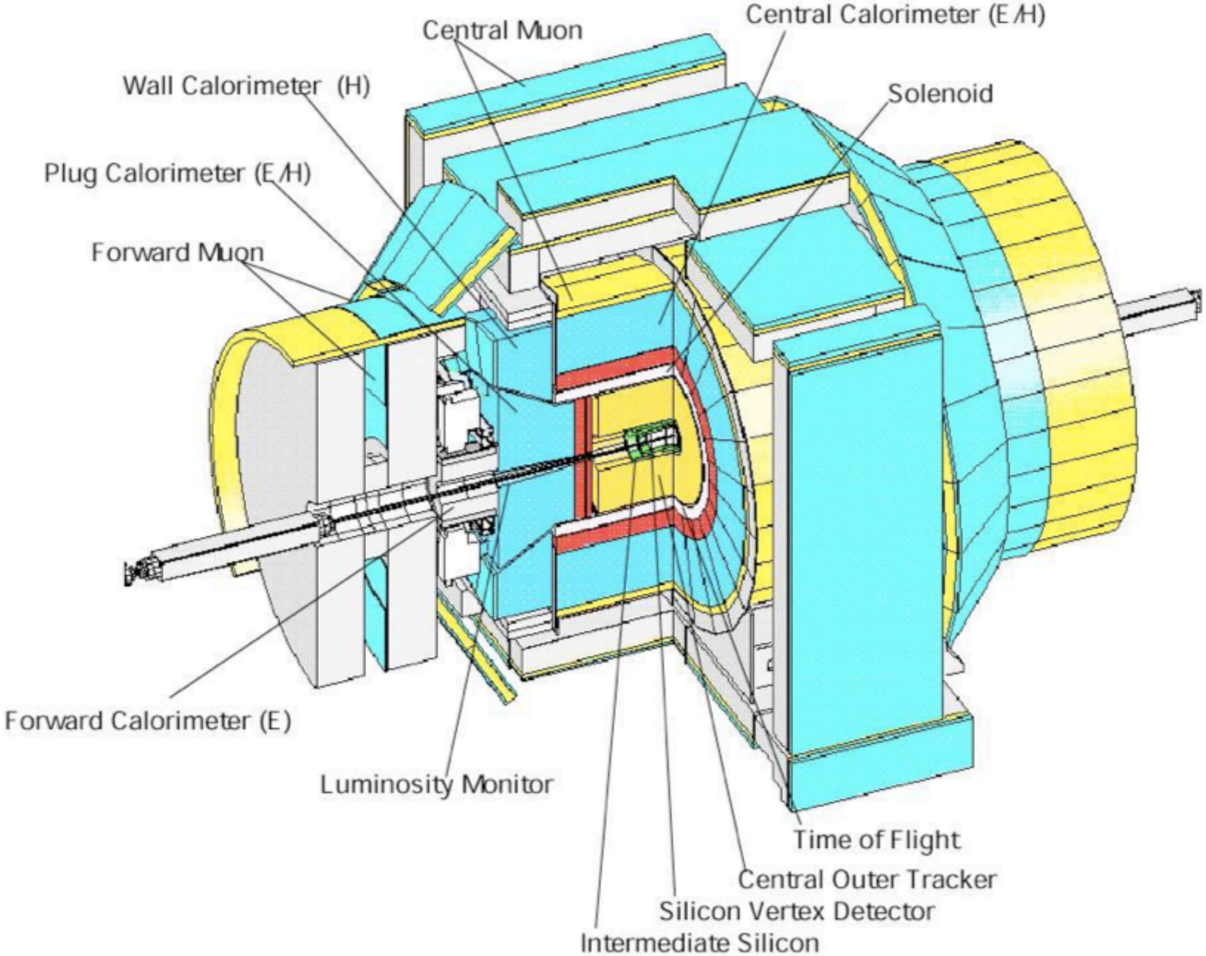


- Produced in 1 fb^{-1}
  - ≈ 6,200,000 $W \rightarrow l\nu + X$
  - ≈ 2,600,000 $Z \rightarrow \nu\nu + X$
  - ≈ 5,100 $WW \rightarrow jjl\nu$
  - ≈ 1,300 $WZ \rightarrow jjl\nu + jj\nu\nu$
  - ≈ 420 $ZZ \rightarrow \nu\nu jj$
  - ≈ 64 $H \rightarrow WW^* \rightarrow l\nu jj$??
  - ≈ 33 $WH \rightarrow l\nu bb$??
  - ≈ 13 $ZH \rightarrow \nu\nu bb$??

$l = e, \mu, \tau$; $M_H = 120$ GeV/c^2

- ~7 fb^{-1} per experiment; ~1.9 fb^{-1} in FY09
- 55-60 pb^{-1} per week in FY09
- Ramping up speed after this summer shutdown
  - Already ~300 pb^{-1} since 09/15
- Running in 2011? Expect 10-12 fb^{-1} per experiment

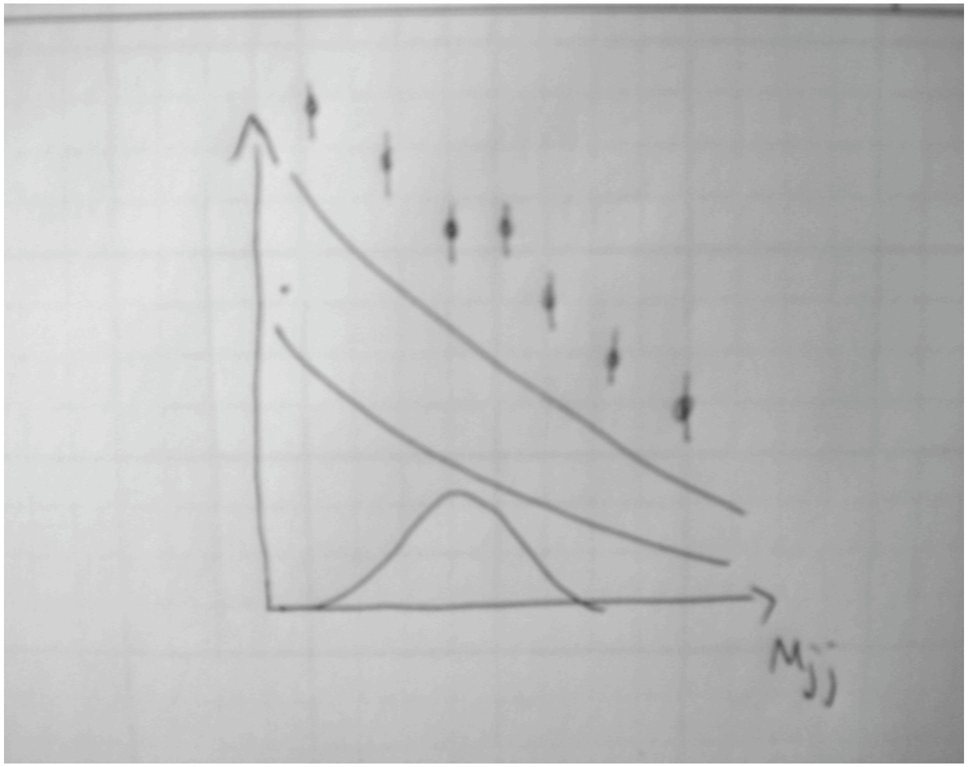
CDF in Run II



- Multipurpose, classic design
- Operating well
  - 80-90% efficiency
- Broad physics program
  - QCD, EWK, top, B-physics, Higgs searches, new physics searches

How Do You Find Dibosons in jj+MET?

- Strategy
  - Select jj+MET events
    - Sensitive to *l*ν and νν decay modes of W and Z
    - Need only Calorimeter & COT (tracking)
      - 10% more data!
  - 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
  - Do it fast!!!

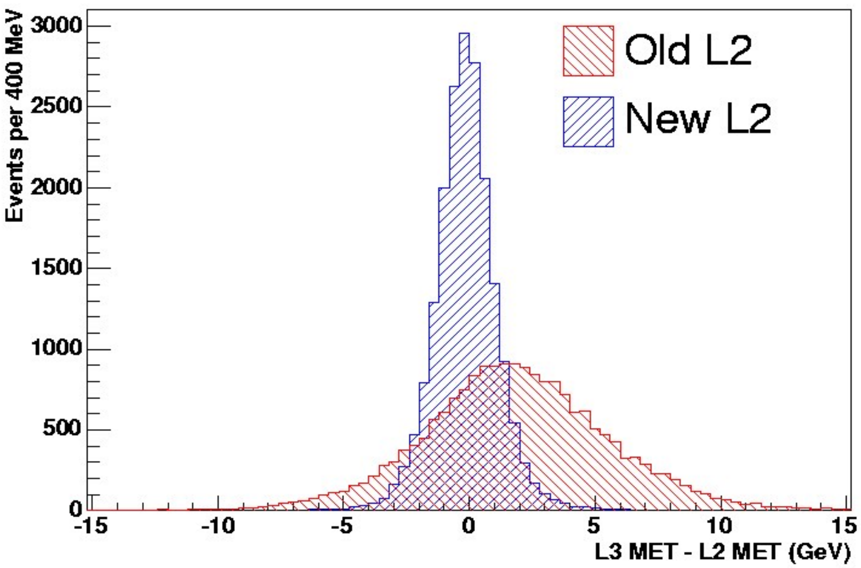


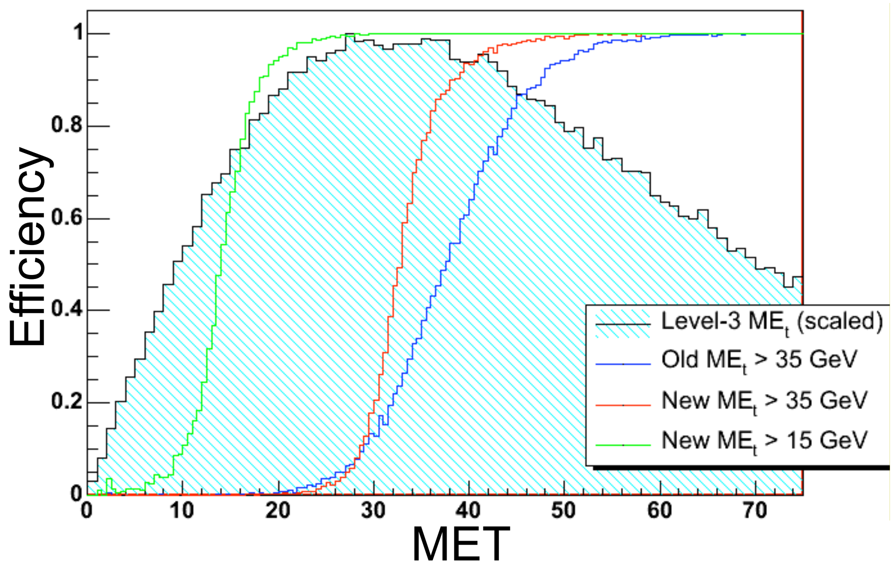
How Do You Find Dibosons in jj+MET?

- Challenges
  - Need lots of data ✔
    - Analysis is based on 3.5 fb^{-1} of data
  - High efficiency triggers at all luminosities
    - L2 trigger upgrade
  - Large backgrounds dominated by QCD multijet events with fake MET and Z/W+jets
    - Sophisticated technique to suppress QCD multijets and estimate systematics
  - Extracting small signal

Calorimeter Trigger Upgrade

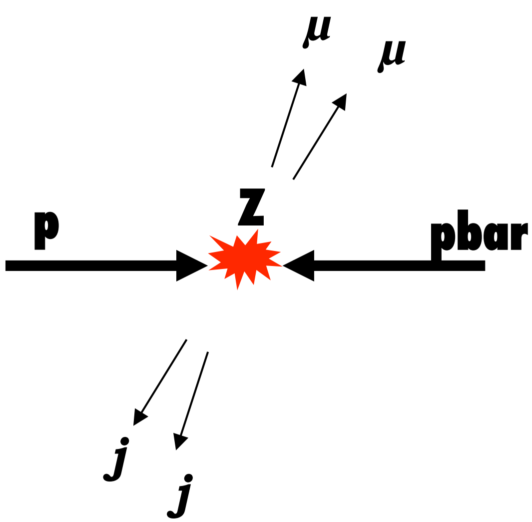
- Upgraded L2 trigger
  - More sophisticated algorithm (almost same as in offline)
  - Better resolution and turn-on
  - Better performance at high luminosity





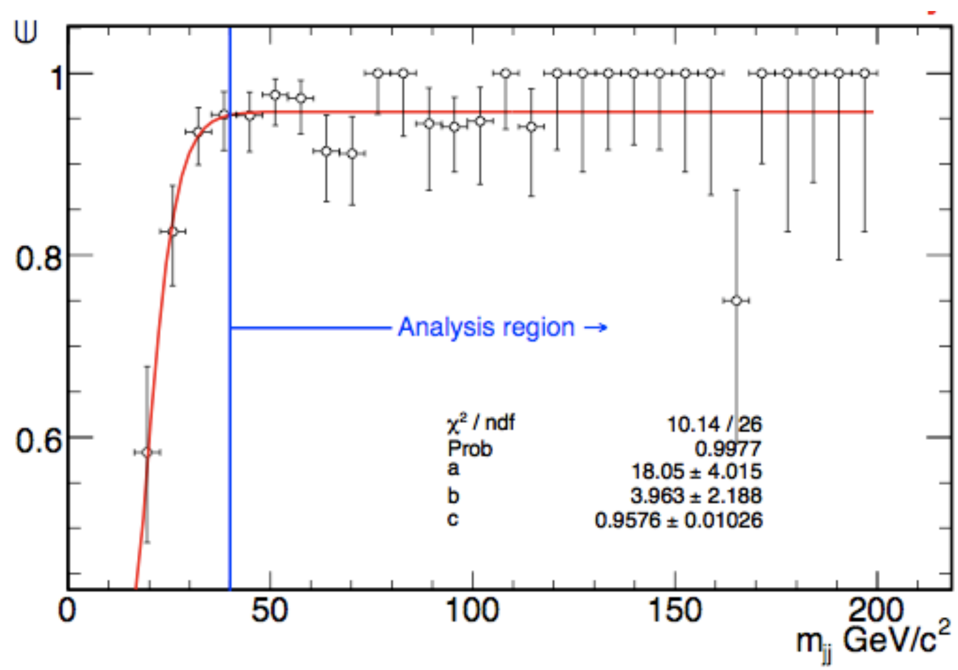
Trigger Efficiency

- Use all MET and MET+jets triggers
  - Every bit of extra data counts!
  - Complicates luminosity accounting
- Use Z→μμ events (standard candle) with two jets from high P_T triggers to find trigger efficiency
  - Integrated efficiency 96.4% ± 2.2%

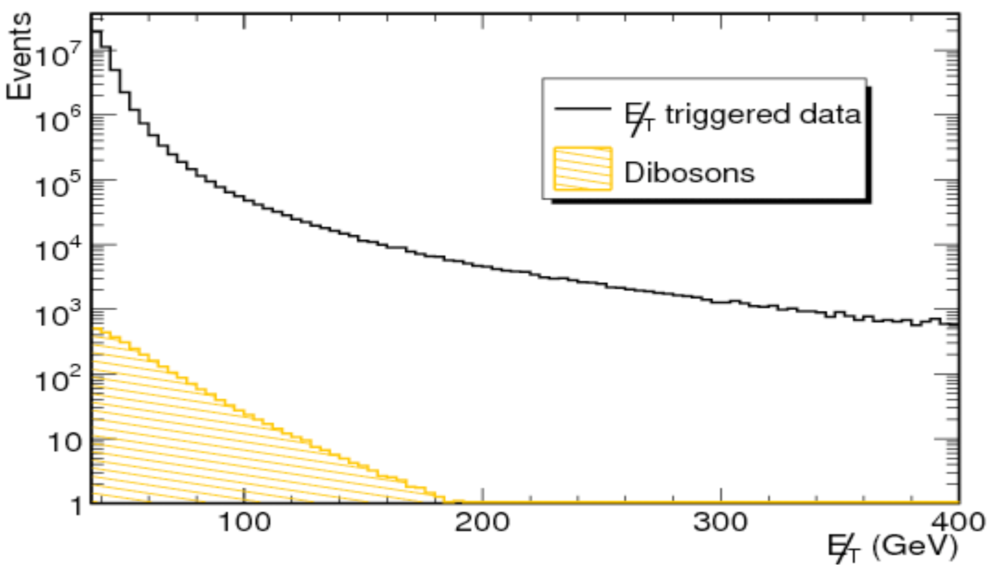


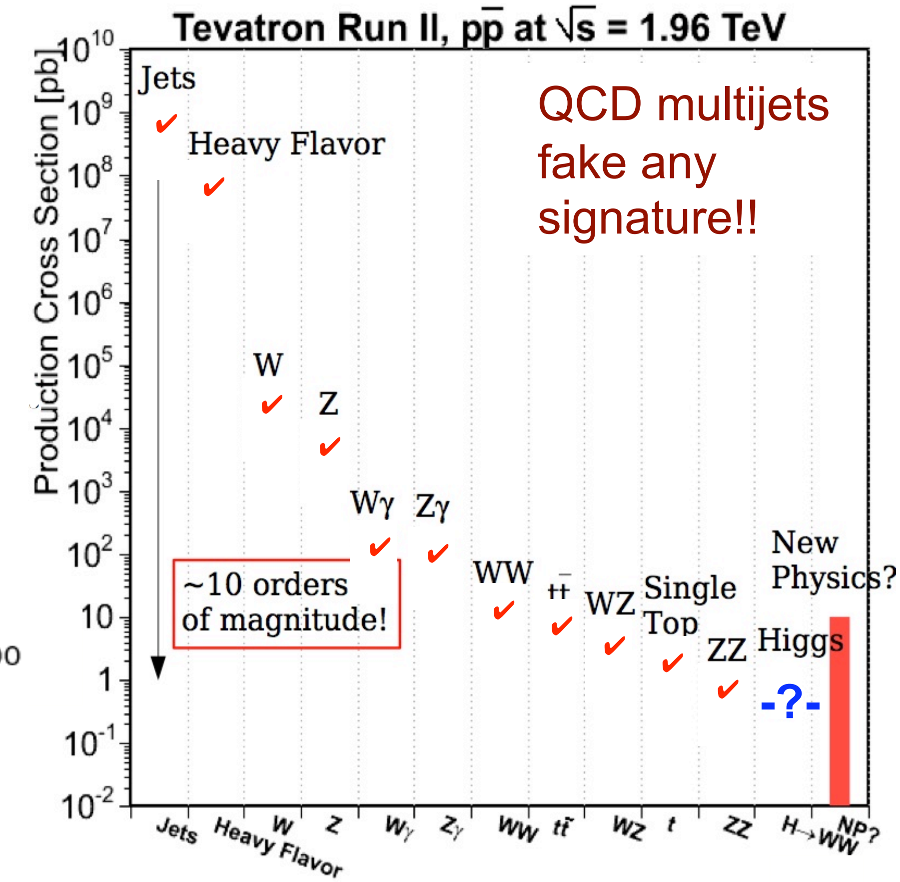
μ is minimum ionizing particle

μ≅MET in calorimeter



Dibosons are Swamped with Backgrounds

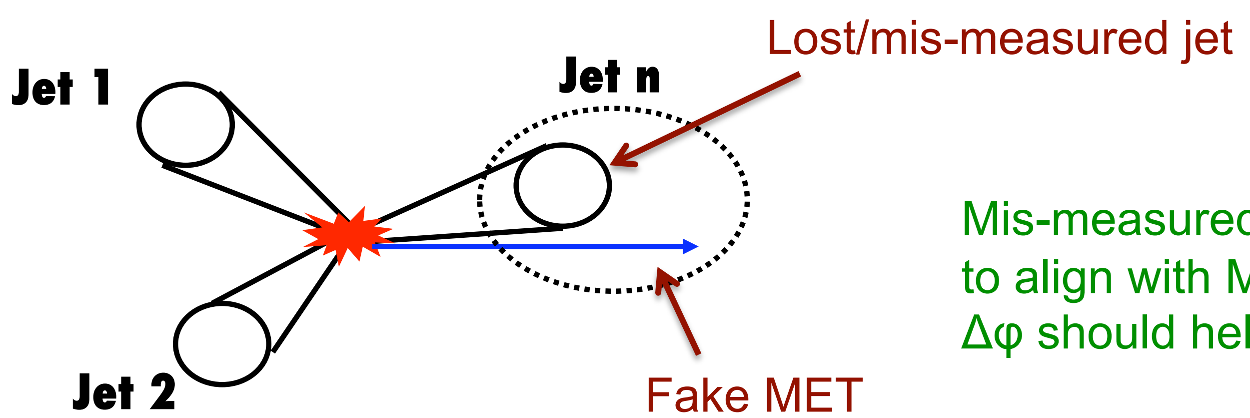




- Triggered data dominated by QCD events with fake MET

Backgrounds: QCD Multijets

- Huge production rate
  – ~9 orders of magnitude above WW+WZ+ZZ
- Fake MET due to jet energy mis-measurement in the calorimeter
  – Rare fluctuations × huge rate = significant background
- Reject as much as possible
- Use data to model whatever remains

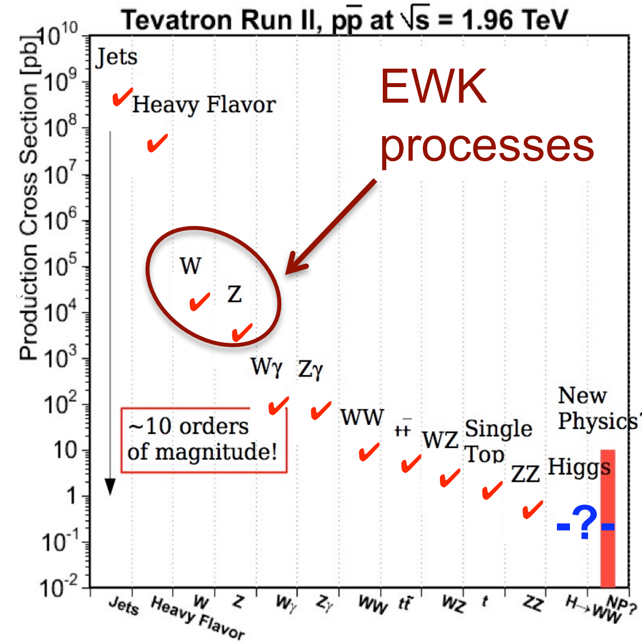


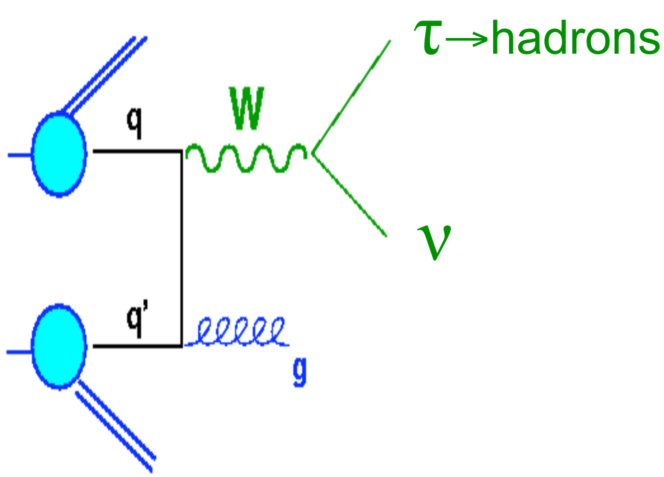
Mis-measured jet tends to align with MET:
$\Delta\varphi$ should help rejection

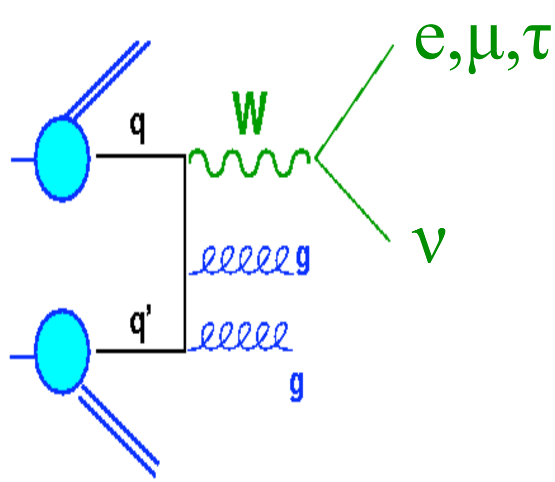
Backgrounds: EWK processes

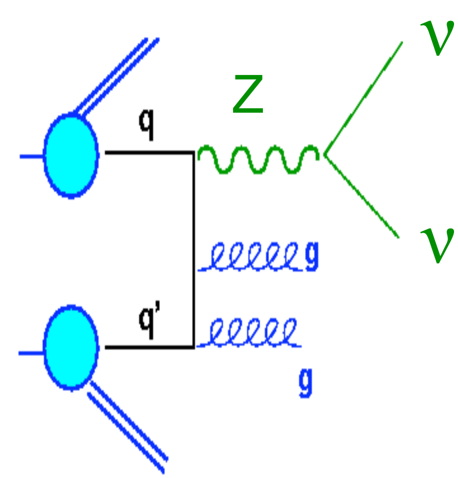
- Use MC to describe kinematics
  - W+jets
    - $W \rightarrow e\nu, \mu\nu, \tau\nu$
  - Z+jets
    - $Z \rightarrow \nu\nu$ (looks like signal)
    - $Z \rightarrow ee, \mu\mu, \tau\tau$
  - Top quark production

Dominant EWK backgrounds





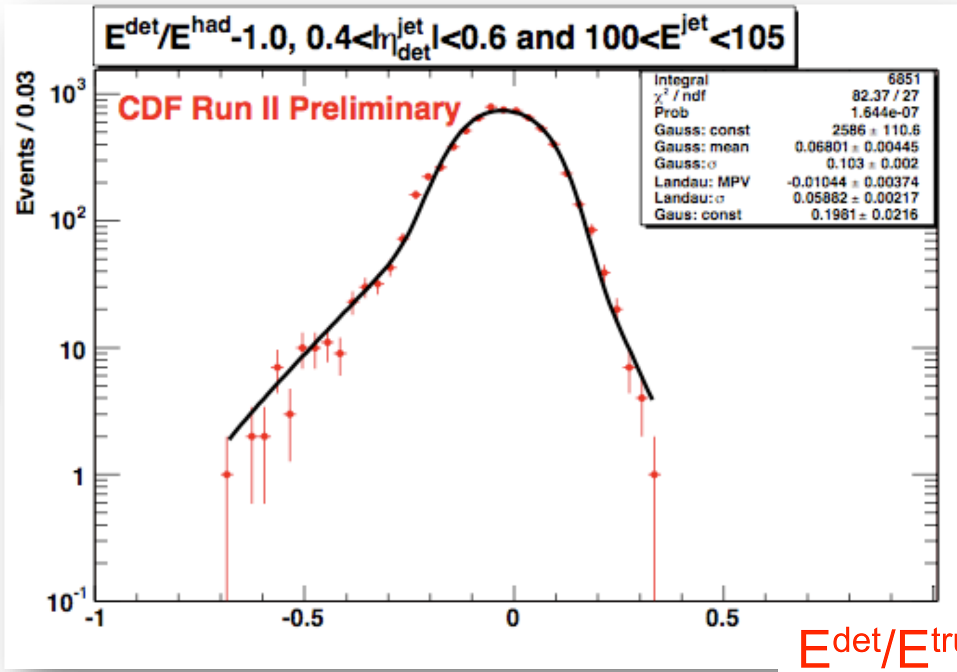




MET Resolution Model (Metmodel)

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

Example of jet energy resolution



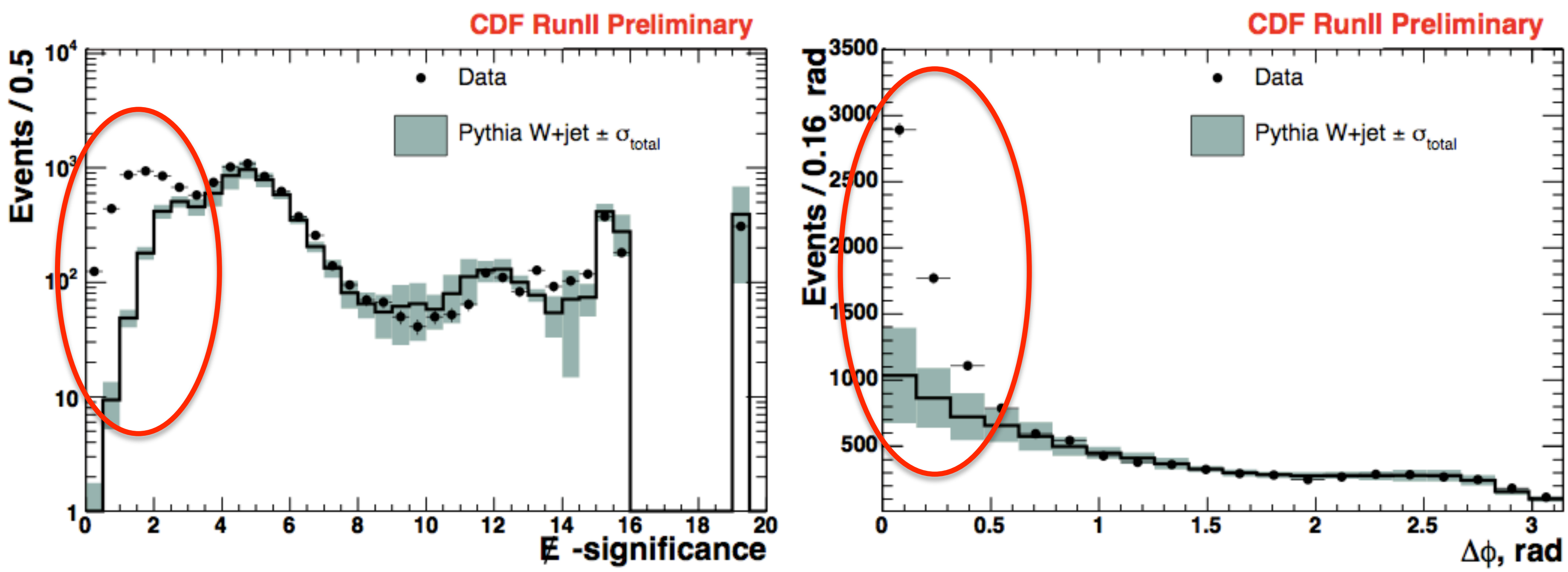
E^{det}/E^{true}-1

Obtain jet energy resolution as function of E^{jet} & η

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

Validation of Metmodel

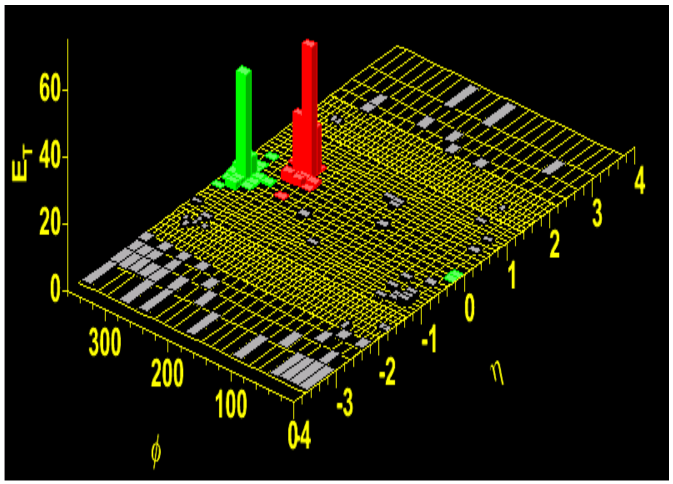
- Use W(→eν)+jet data to validate MET-resolution



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

Diboson Candidate Selection: 44,910 events

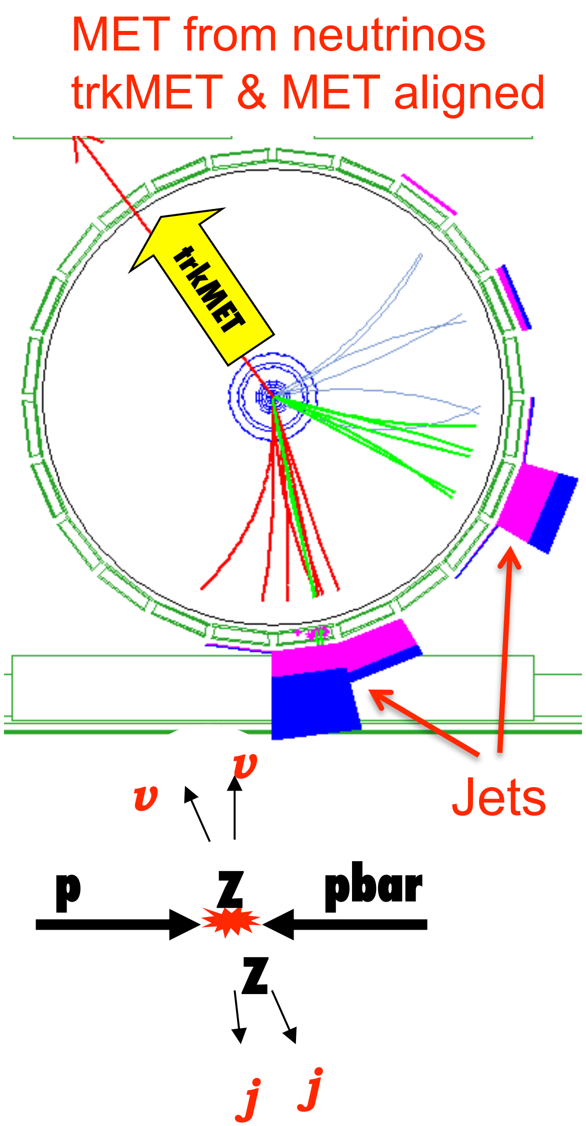
- Analysis is based on 3.5 fb^{-1} of data



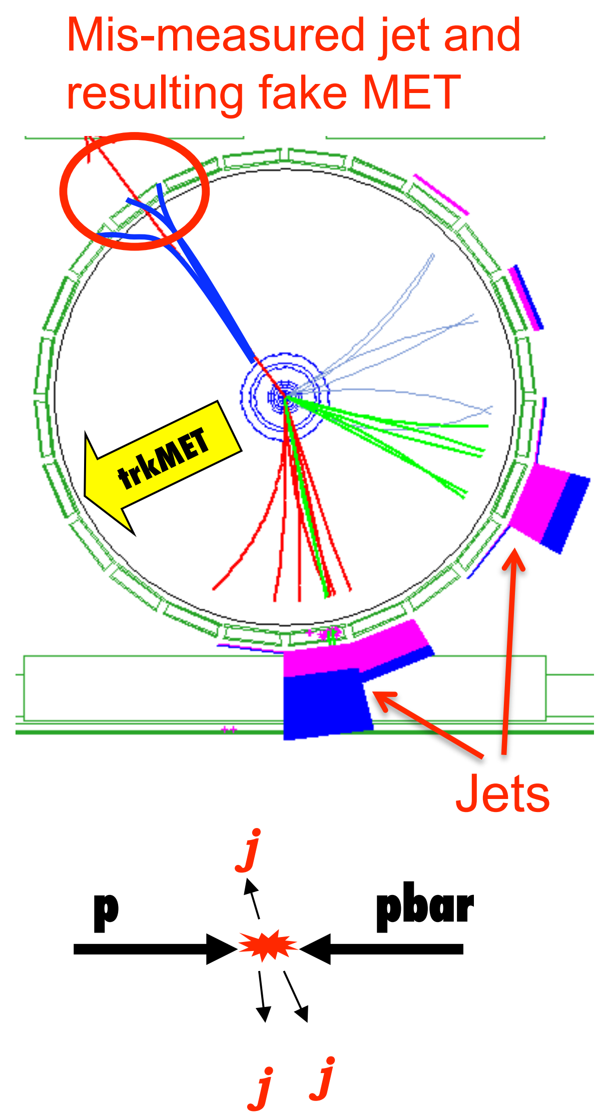
QCD multijet rejection

Variable	Cut values
MET	>60 GeV
Jet -1,2 E_T	>25 GeV
Jet EmFr	<0.9
Jet -1,2 $\|\eta\|$	<2.0
$\Delta\phi_{closest}$	>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

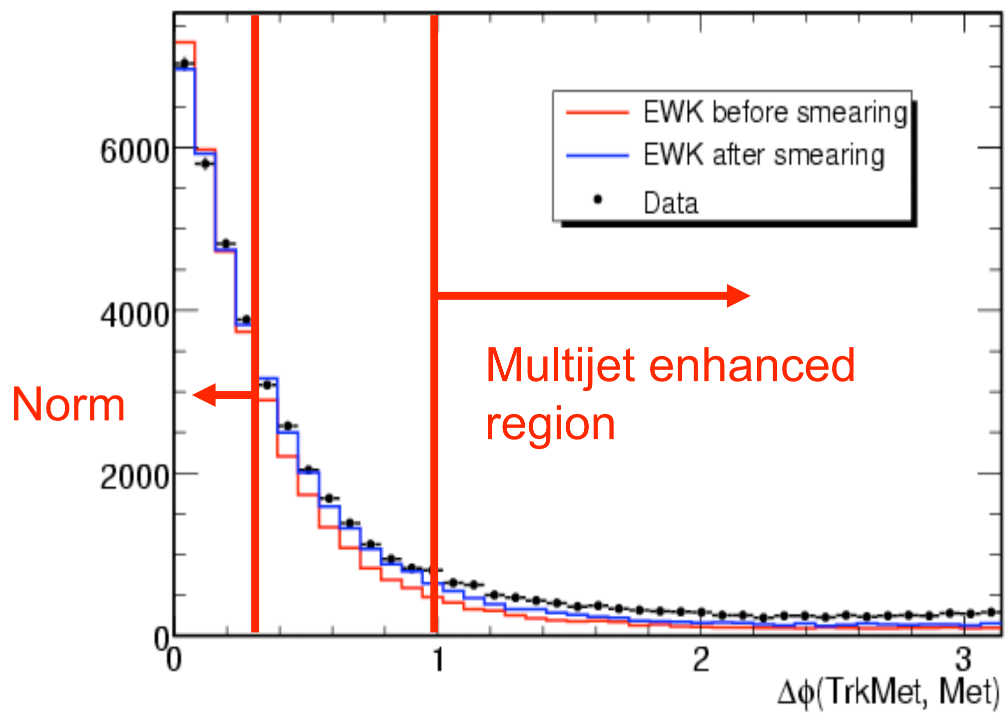
Modeling Remaining Multijet Background



- Track MET (trkMET)
  - Analogous to MET
- True MET
  - Small Δφ(trkMET-MET)
- Fake MET
  - Large Δφ(trkMET-MET)



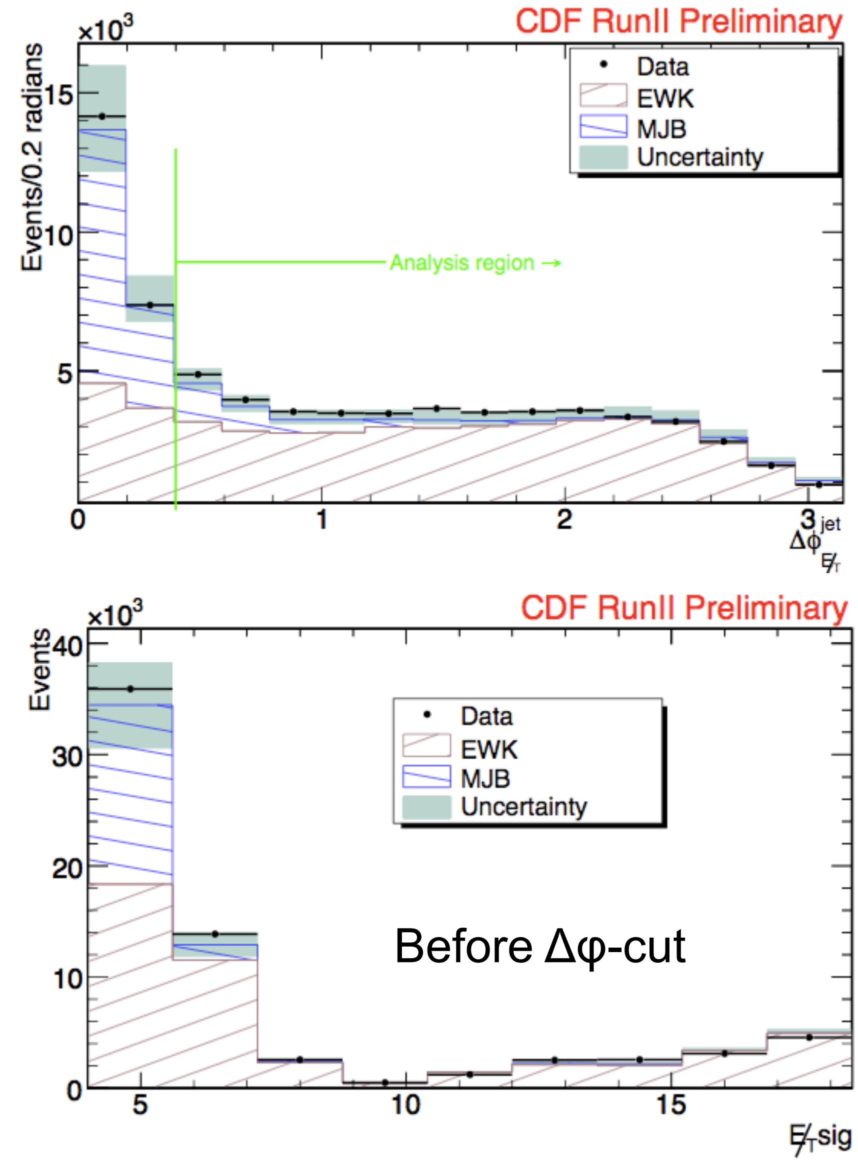
Modeling Remaining Multijet Background



- Subtract EWK from data in $\Delta\varphi$(trkMET-MET)>1.0 region
- Account for QCD background contribution in peak with dijet MC
- Address MC-data differences in resolution with $Z \rightarrow \mu\mu$ events

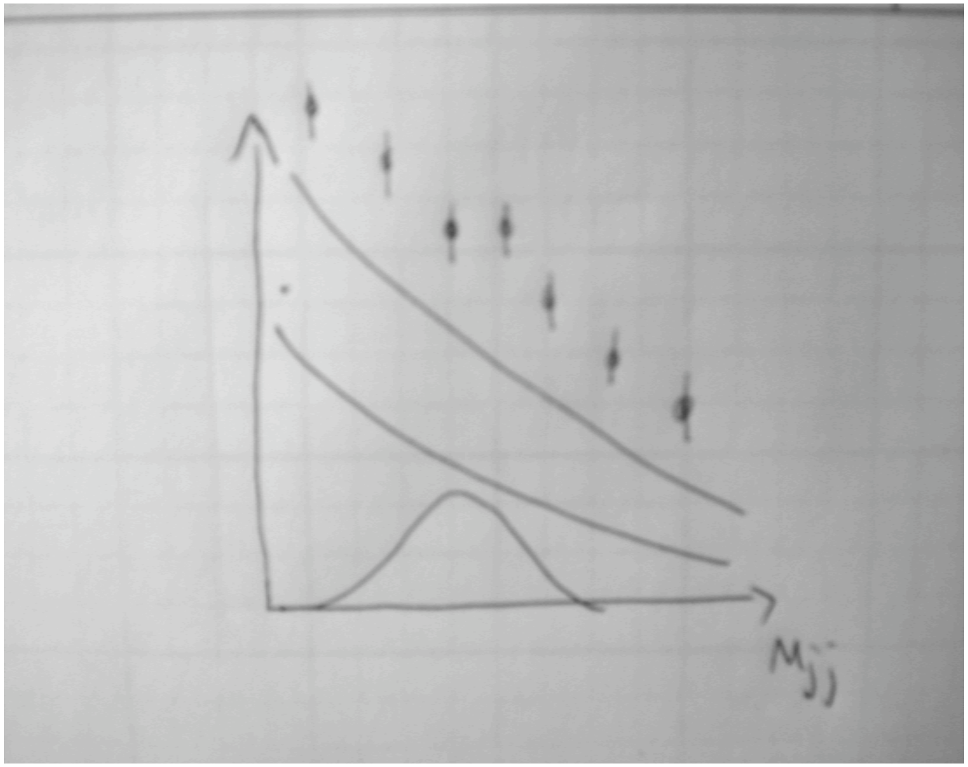
Checking Background Model

- Great agreement in distributions sensitive to fake MET
  - MET-significance
  - Δφ(closest)
- EWK background and signal have same shapes

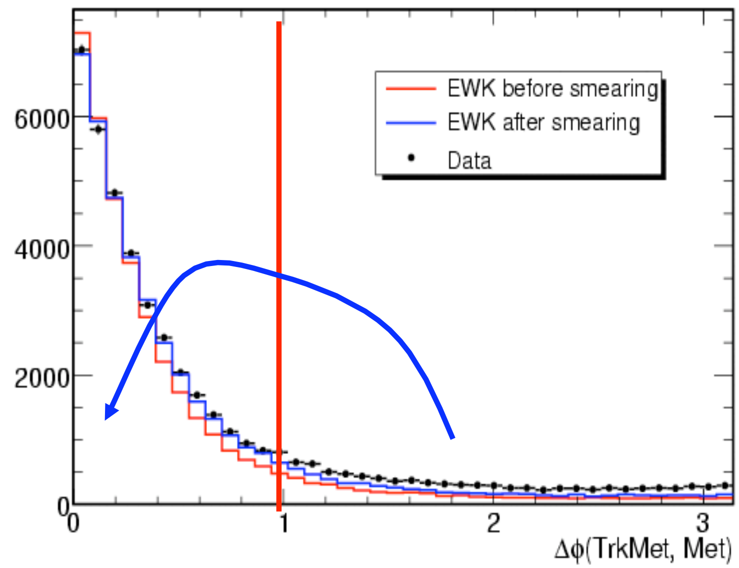


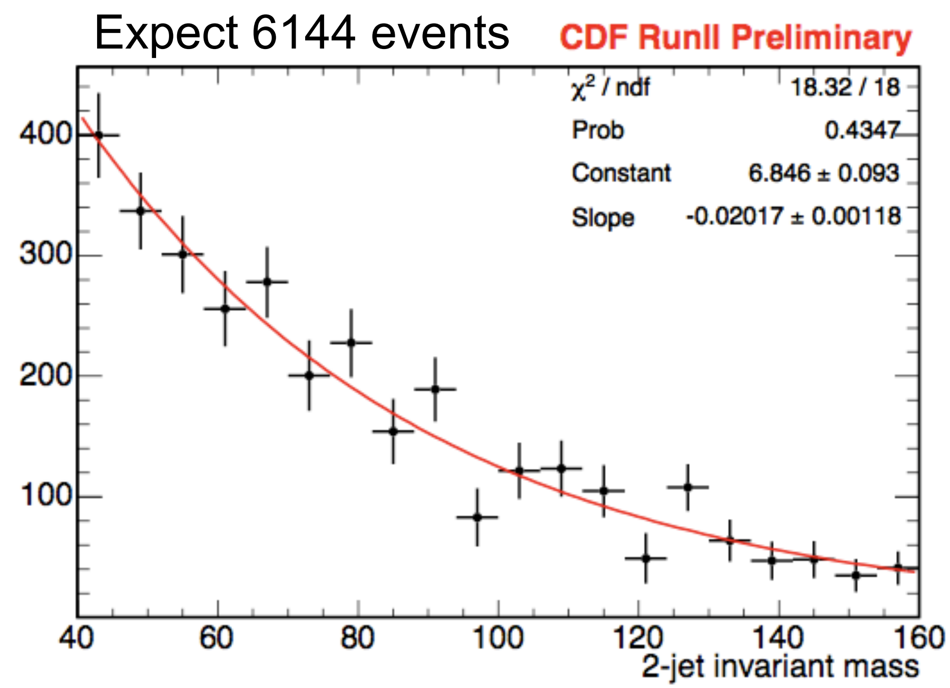
Extracting Diboson Signal

- Fit M_{jj} distribution using three templates
  - EWK, QCD, signal
- Minimize the unbinned extended negative log likelihood (ROOFIT)
- Nuisance parameters in the fit
  - EWK normalization
  - Jet energy scale (JES)
  - QCD shape & normalization
  - Signal normalization



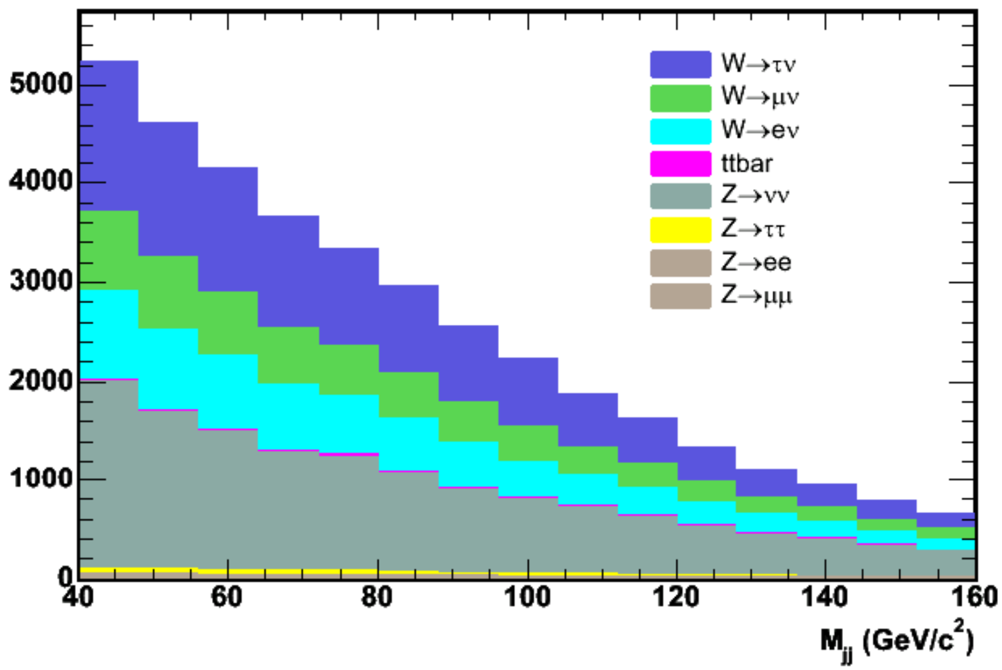
M_{jj} Templates: Multijet Background





- Shape & normalization taken from data in the region $\Delta\varphi$(trkMET-MET)>1.0 after EWK subtraction
- Shape & normalization are constrained in M_{jj} fit
- Uncertainties are driven by extrapolation into $\Delta\varphi$(trkMET-MET)<1.0 region

M_{jj} Templates: EWK Background



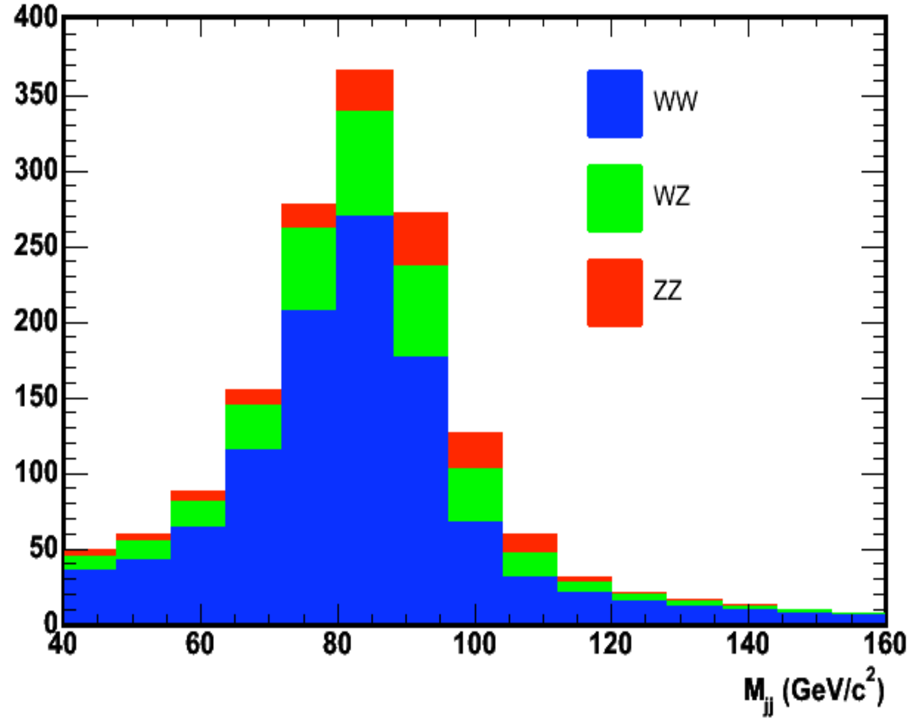
- Shapes taken from MC
- Total number of EWK events is unconstrained in fit

Expected 36,906 EWK events

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	**82.9**

M_{jj} Templates: Signal

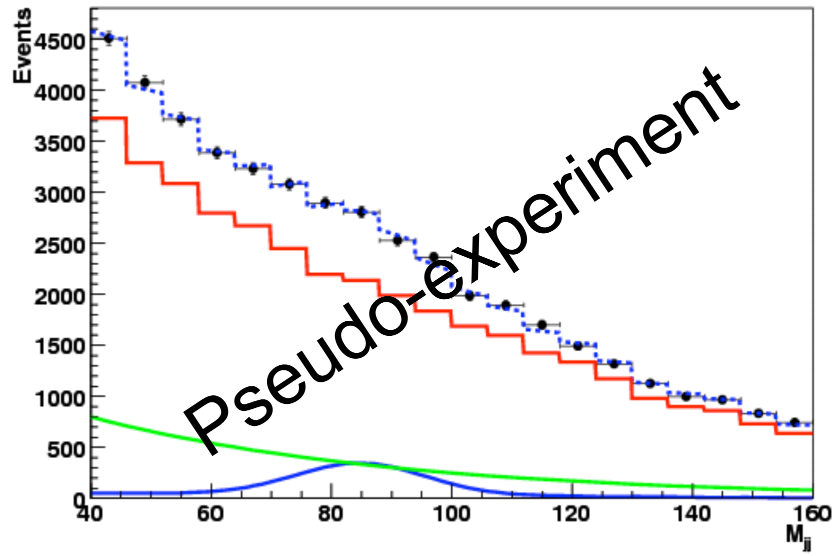
Process	Expected % of sample
WW	2.3
WZ	0.7
ZZ	0.3
Total Signal	3.3
EWK	82.9
QCD	13.8

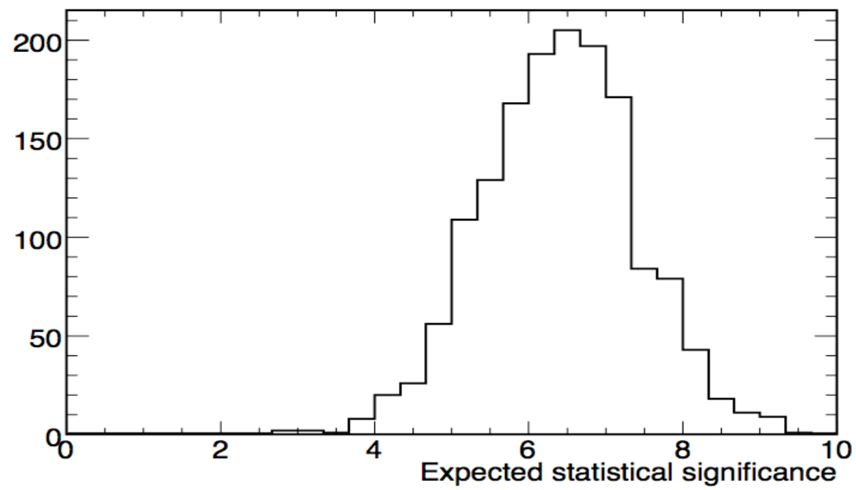


- Shape from MC (Gaussian + polynomial)
- Number of signal events is unconstrained in fit
- Jet energy scale has a Gaussian constraint in fit
  - Gaussian width depends linearly on JES

Expected Signal Significance

- Check with pseudo experiments (PE)
- PE's input from expectations
  - EWK: 36,906
  - QCD: 6,144
  - Signal: 1,480
- Expected mean statistical significance ~6σ





Systematics

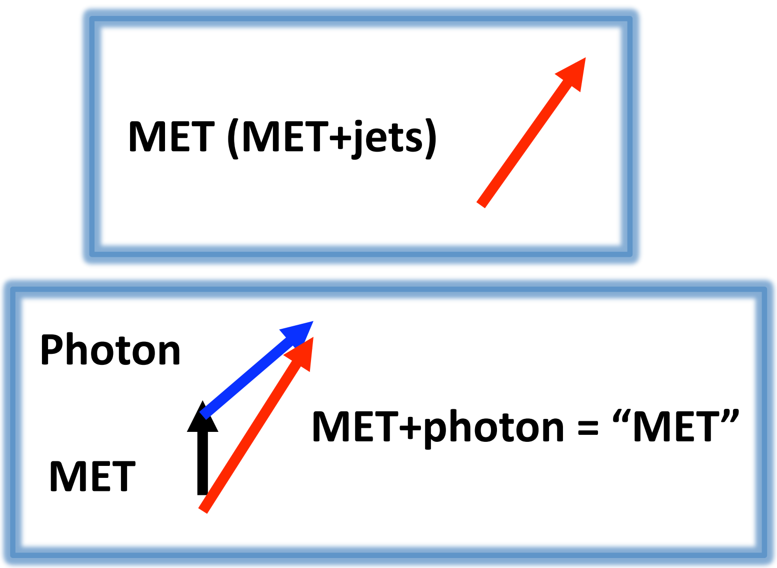
Signal Extraction	% uncertainty	# of signal
EWK shape	7.7	117
Resolution	5.6	85
TOTAL EXTRACTION	**9.5**	**144**
Acceptance	**% uncertainty**	**# of signal**
JES	8	121
JER	0.7	11
Met Model	1	15
Trigger Efficiency	2.2	33
ISR/FSR	2.5	38
PDF	2	30
TOTAL ACCEPTANCE	**9.0**	**136**
LUMI	**6**	**91**
TOTAL SYSTEMATICS	**14.4**	**218**

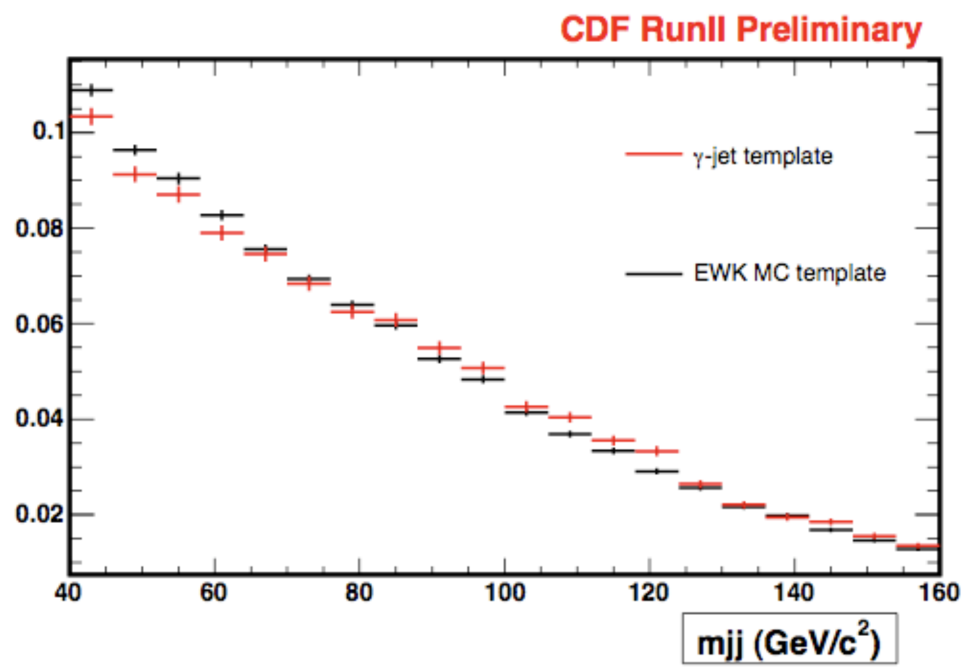
- Uncertainties associated with nuisance parameters are folded into fit statistical uncertainty
- Remaining systematic uncertainties on signal extraction
  - EWK shape (next slide)
  - Jet energy resolution (JER)
    - Smear signal template according to JER uncertainty

Systematics on Shape of EWK Background

- Use data γ+jets as alternative template
  - Many uncertainties eliminated
- Basic idea: kinematics of **V+jets ≈ γ+jets**, V=W,Z

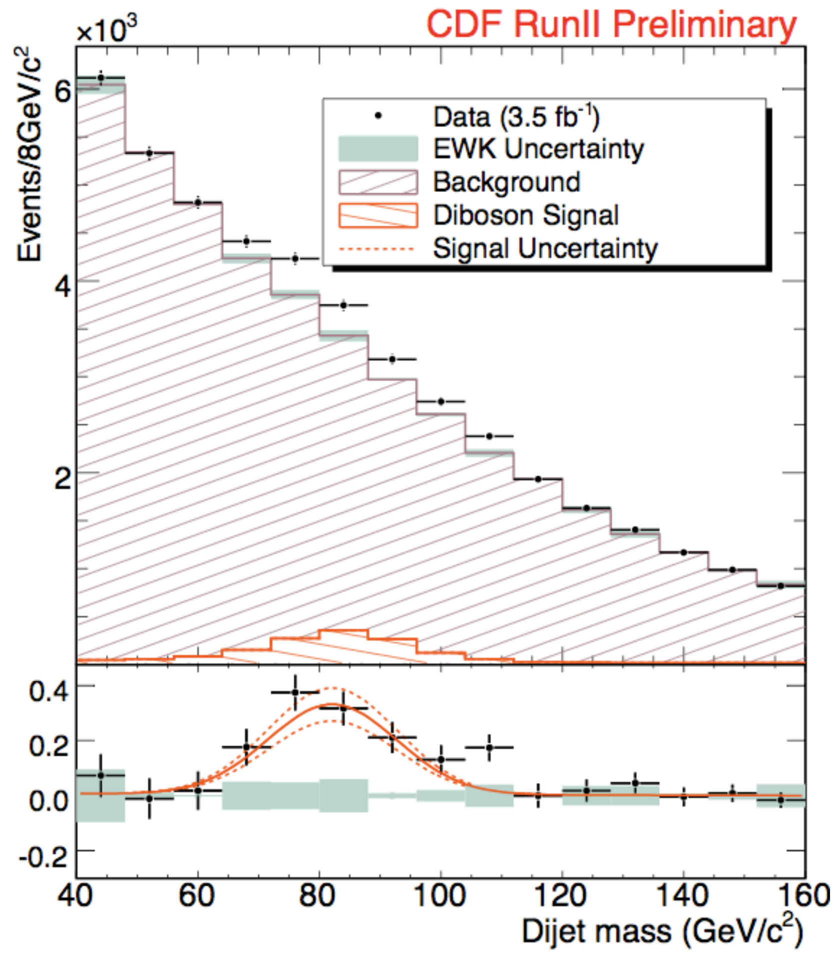
$$V + jets(data) = \frac{V + jets(MC)}{\gamma + jets(MC)} \times [\gamma + jets(data)]$$





Signal Extraction

- Fit result
  - Signal: 1516 ± 239(stat) ± 144(syst)
    - Expected from PE: 1398 ± 243
  - JES: 0.985 ± 0.015
- Significance
  - Naively $1516/\sqrt{(239^2+144^2)}=5.4\sigma$
  - Consider parameter variations for all sources of systematics
    - Compare likelihood of background only fit with full fit result
    - Convert difference into probability
  - **Lowest significance returned: 5.3σ**



χ^2/ndf has 37% probability

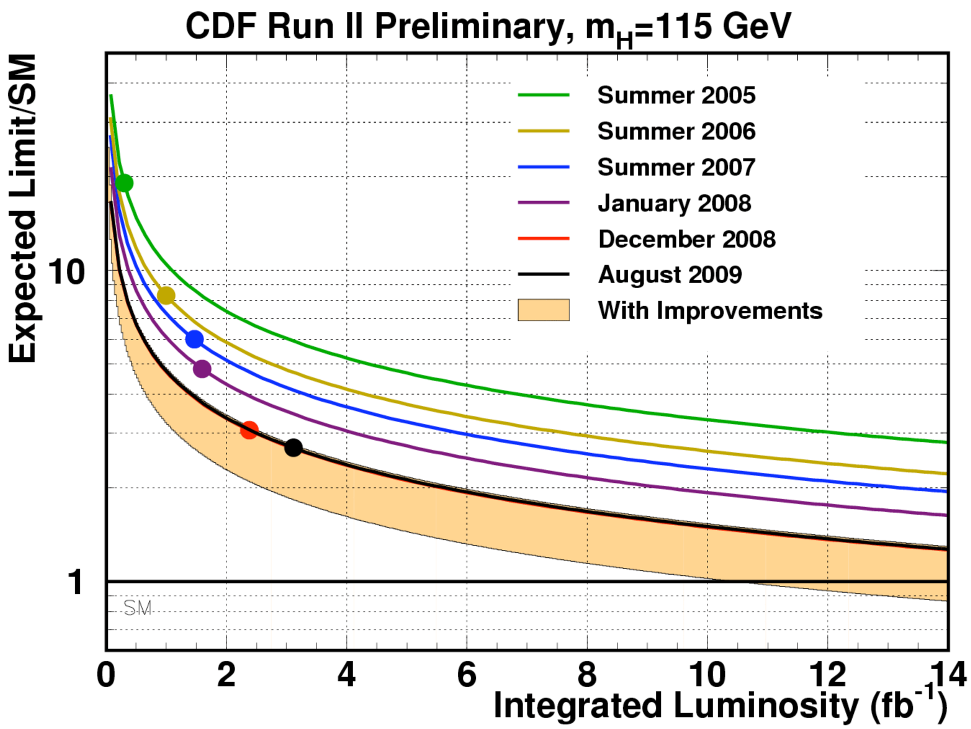
Cross Section

$$\sigma = \frac{N_{VV}(extracted)}{\varepsilon \cdot A \cdot L}$$

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

- N_{VV}(extracted)=1516
- Efficiency, ε
  - Trigger: 96%
  - Cosmics removal: 99%
- Luminosity, *L*: 3,450 pb^{-1}
- Acceptance is weighted by WW, WZ, ZZ cross sections
- Cross section
  - Measured: 18.0 ± 2.8(stat) ± 2.4(syst) ± 1.1(lumi) pb
  - Theory: 16.8±0.5 pb

Back to Higgs Searches…

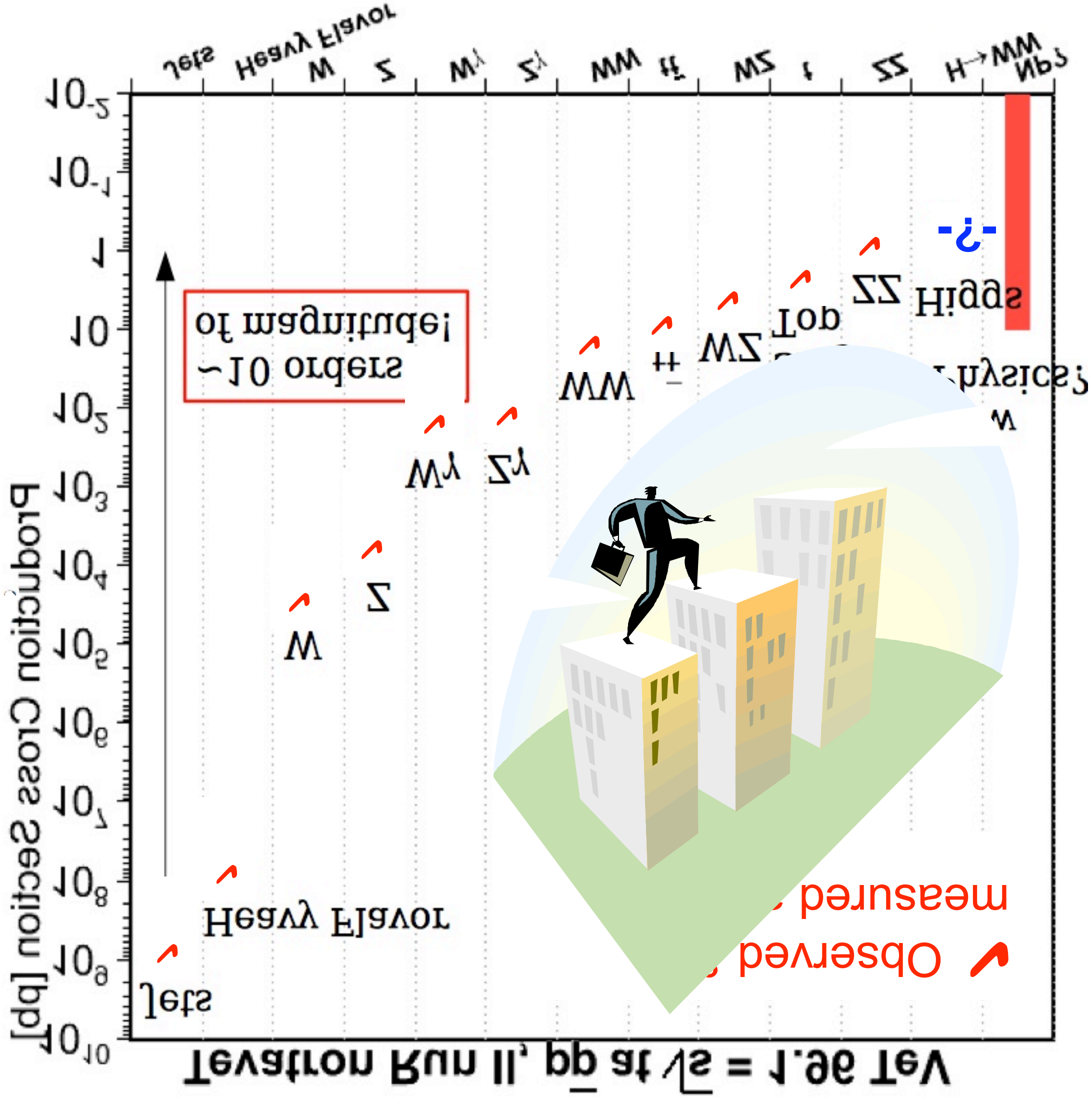


- On the road to Higgs
  - Need more data
    - Tevatron running until 2011?
    - Increase acceptance
  - Need better analysis techniques
    - Metmodel, track MET, …
  - Reduce systematics
    - Use data to model backgrounds
  - Need smart techniques to extract small signals
    - ME, neural net, decision trees
  - Combine analyses
  - Explore new channels

Summary

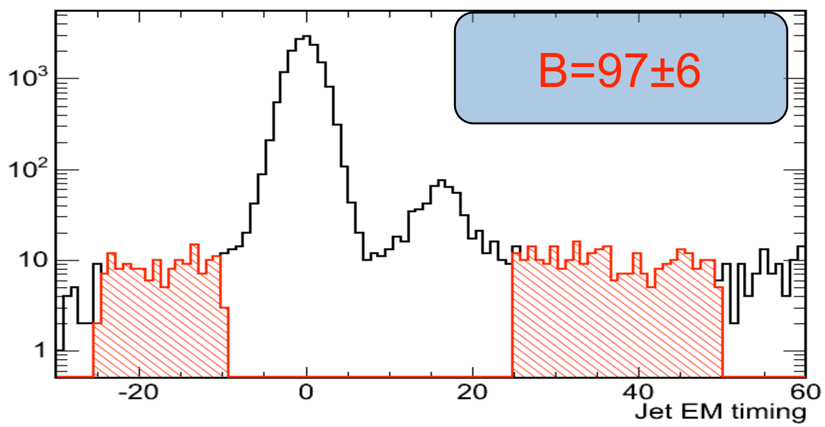
- First observation of vector boson pair production in hadronic final state at the Tevatron
  - Published in PRL 103, 091803 (2009)
  - Milestone in search for low mass Higgs
- Measured diboson production cross section
  - Measured: 18.0 ± 2.8(stat) ± 2.4(syst) ± 1.1(lumi) pb
  - SM prediction: 16.8±0.5 pb
- Developed and tested new effective techniques
  - Metmodel to remove QCD
  - Track MET to estimate remaining QCD
  - Used γ+jj events to estimate shape systematics of EWK template
- Next goal before Higgs is WZ and ZZ observation in final state with two b-jets

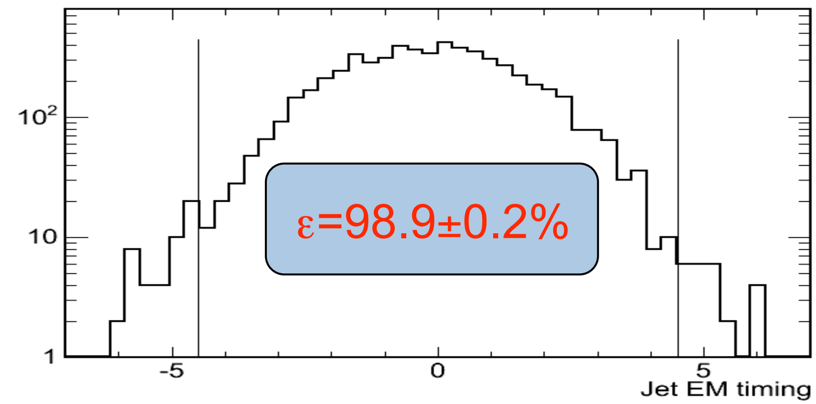
We are almost at the summit of SM!!!

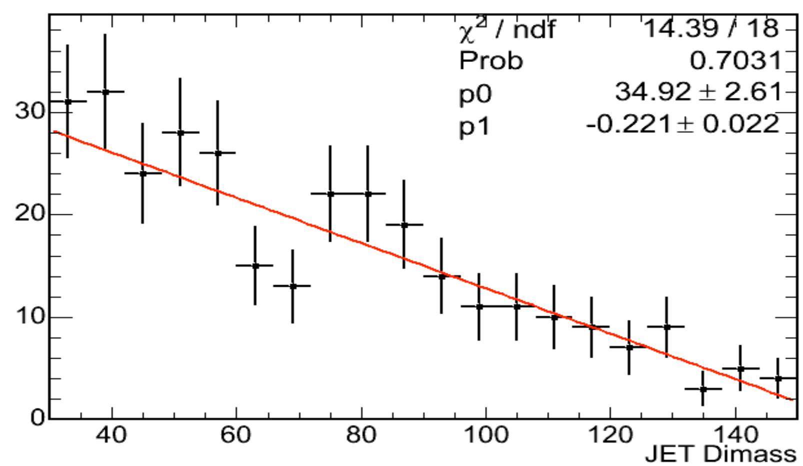


Backup Slides

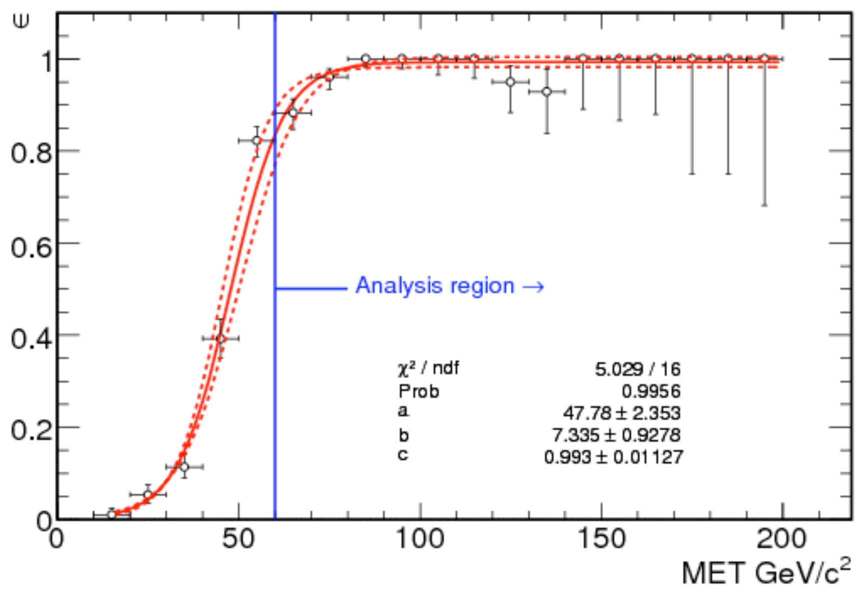
Cosmic Removal

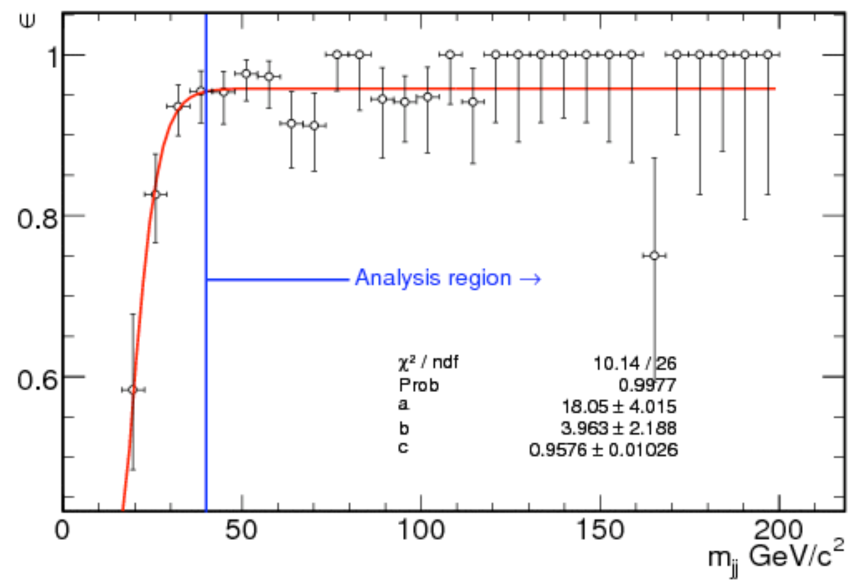






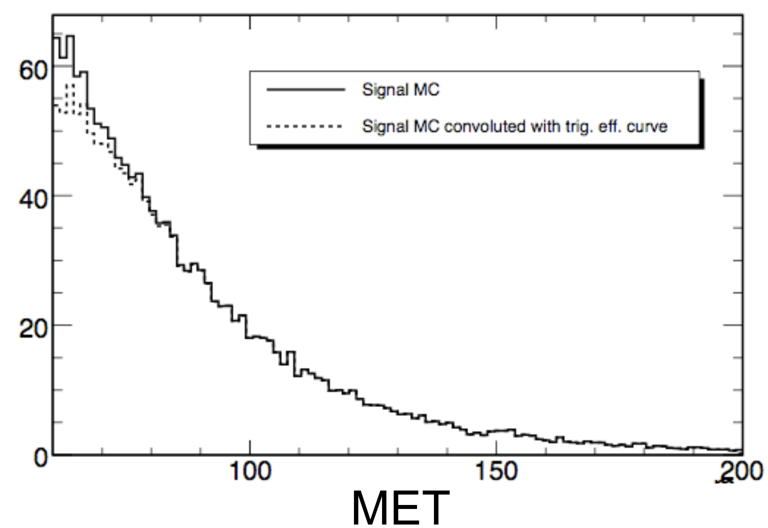
Trigger Efficiencies



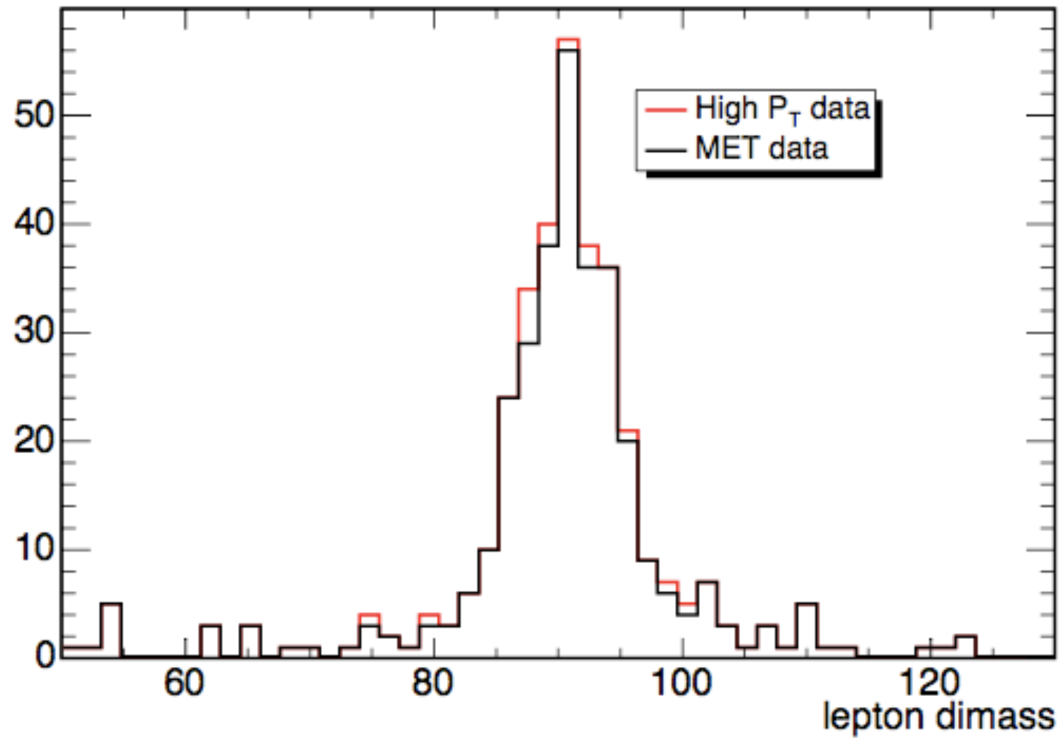


- Final integral efficiency is 96.2%±2.2%
  - Take 90% efficiency for MET>120 → 2% effect → assign additional 2% uncertainty

$$Eff = \frac{c}{1 + e^{\frac{a-x}{b}}}$$

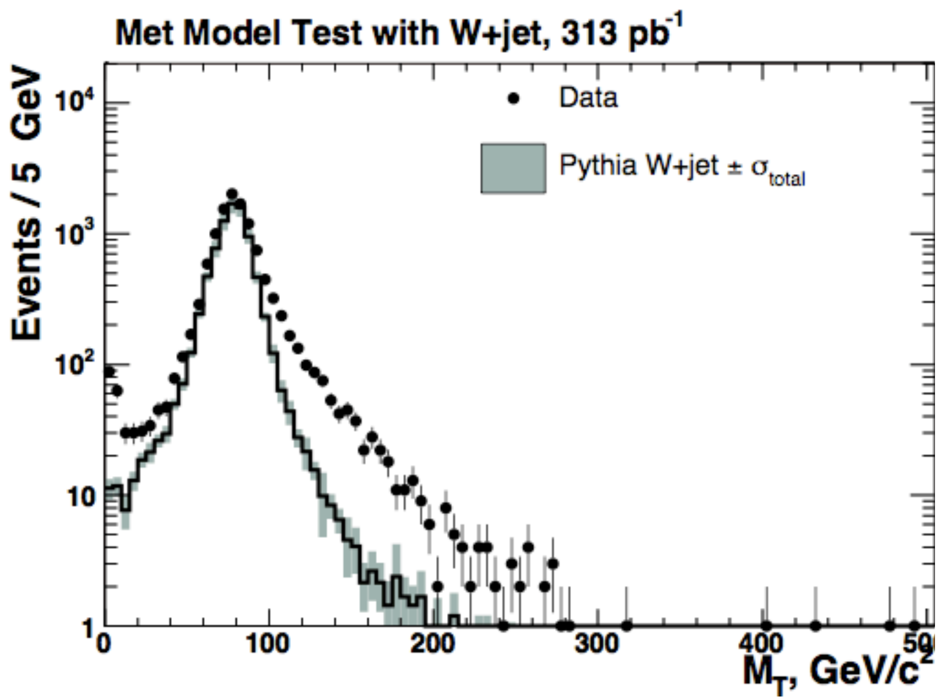


"Effective" Sample Lumi: 3,450 pb^{-1}

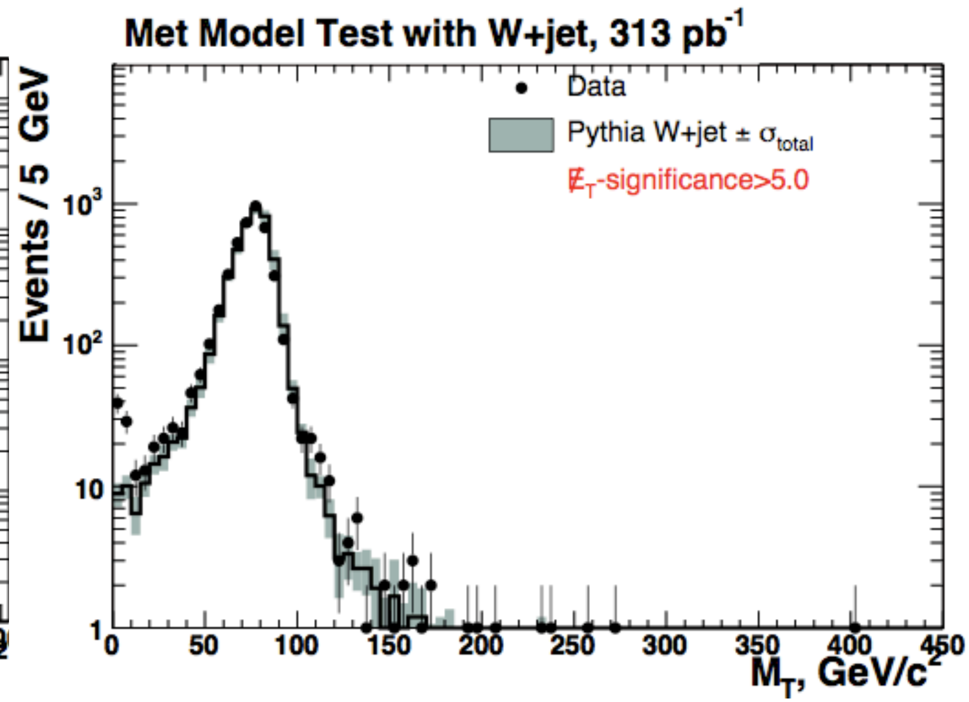


- Use muon trigger to find "effective" lumi of all MET triggers
  - Muon sample: $N = \sigma * A * \varepsilon * L_{HiPt} = 357$, $L_{HiPt} = 3{,}483\ pb^{-1}$, $\varepsilon = 100\%$
  - MET sample: $N^{MET} = \sigma * A * \varepsilon^{MET} * L_{MET} = 339$, $\varepsilon^{MET} = 96\%$
  - $L_{MET} = L_{HiPt} * N^{MET} / (N * \varepsilon^{MET}) = 3{,}450\ pb^{-1}$
  - Method also x-checked with MET40 & MET45 triggers only

Rejecting Fake MET in W+jet Events: M_T plot



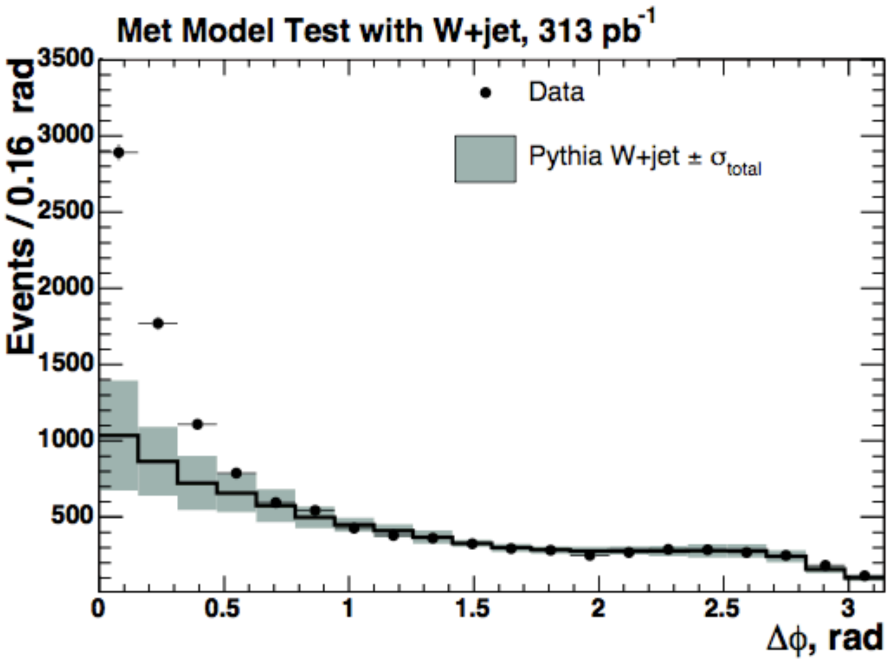
All events



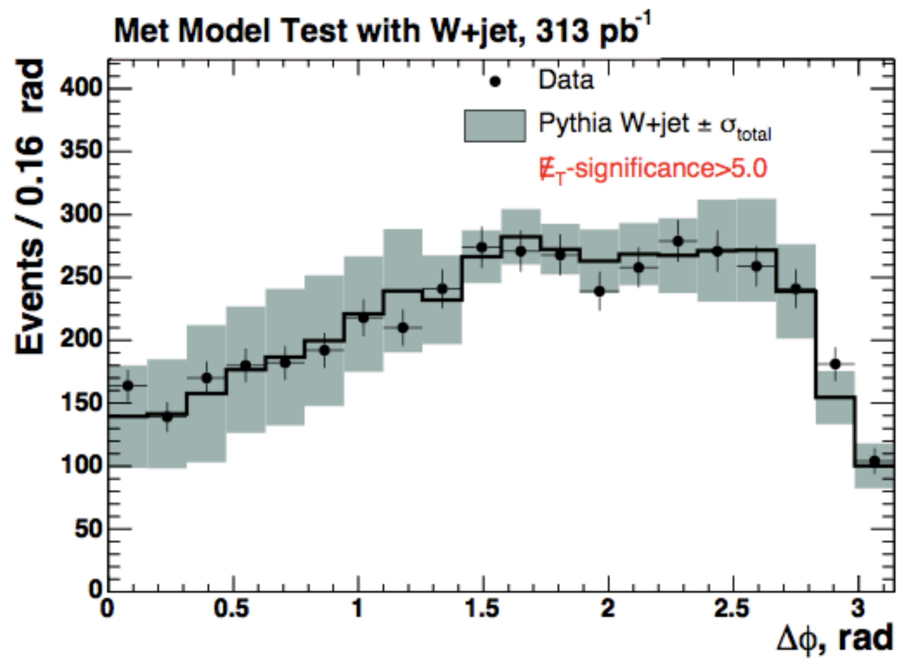
Events after MET-sig>5

- Metsig>5 effectively removes QCD fakes
  - Only a small fraction remains in the region M_T<10 GeV

Rejecting Fake MET in W+jet Events: $\Delta\varphi_{closest}$



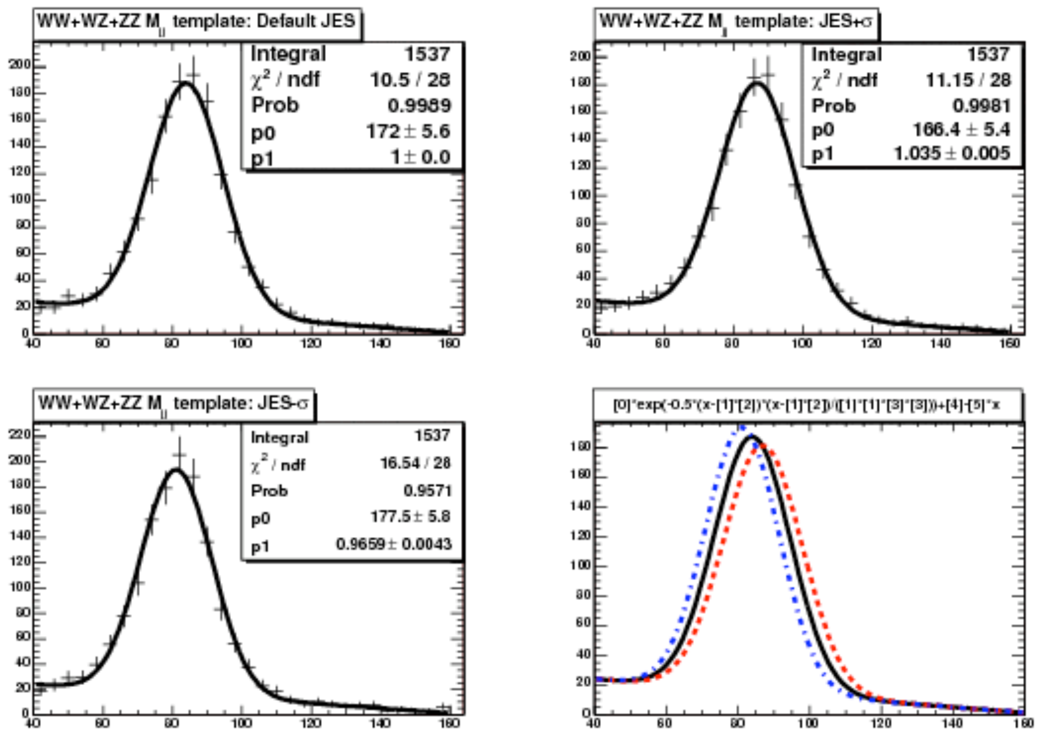
All events

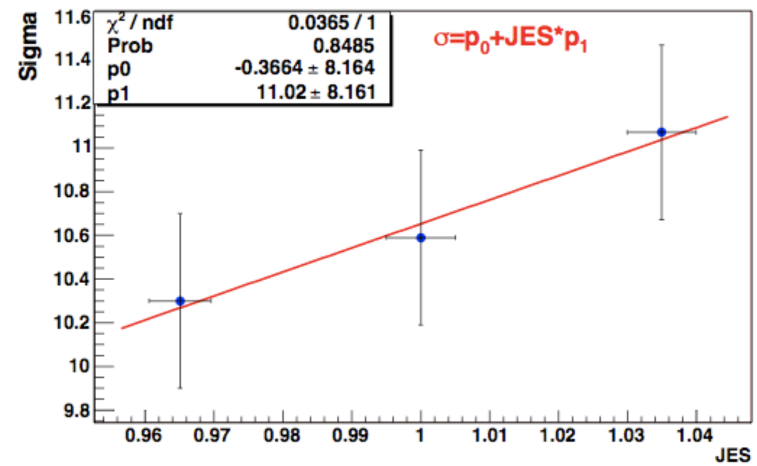


Events after MET-sig>5

- Left plot: clearly see QCD contribution at small $\Delta\varphi$
- Right plot: QCD is gone if MET-sig>5

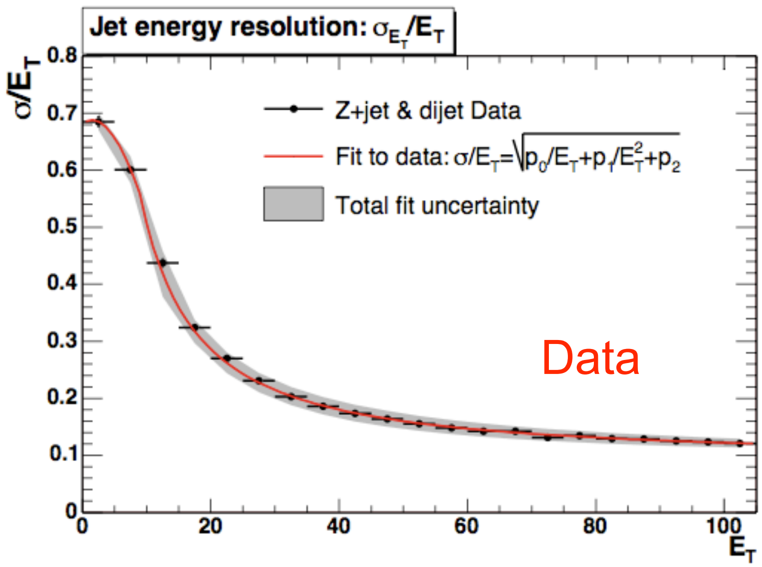
Signal Template for Final Fit

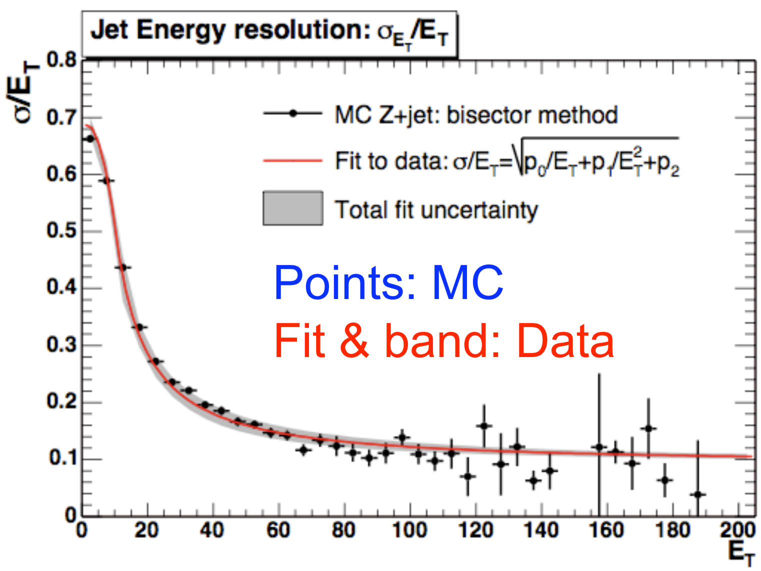


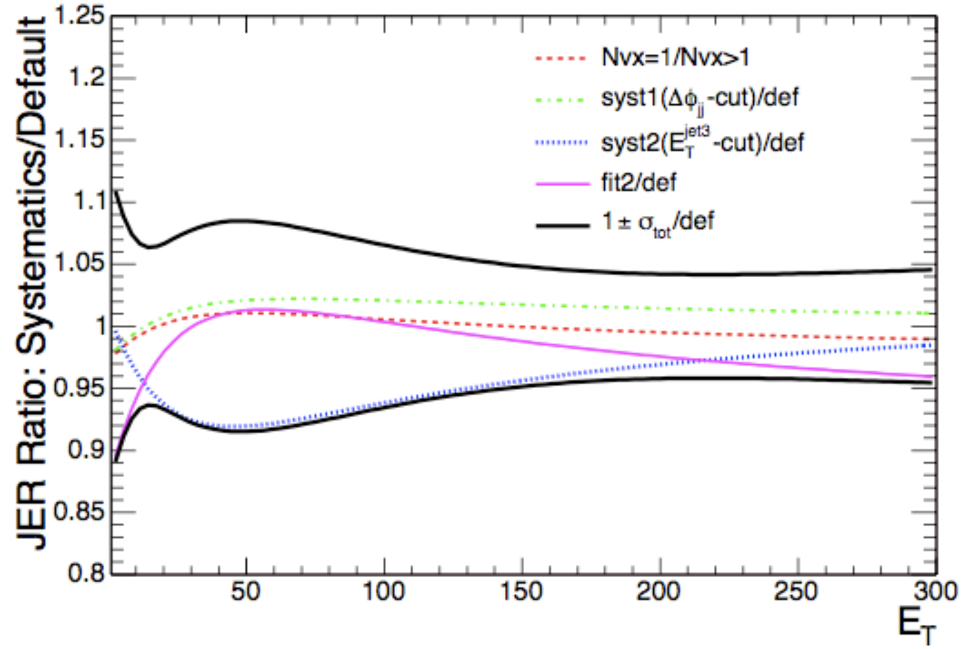


- Allow JES to float in the fit
  - From Final fit: 0.985±0.019
- Parameterize width (Gaussian σ) as a function of JES

JER uncertainty

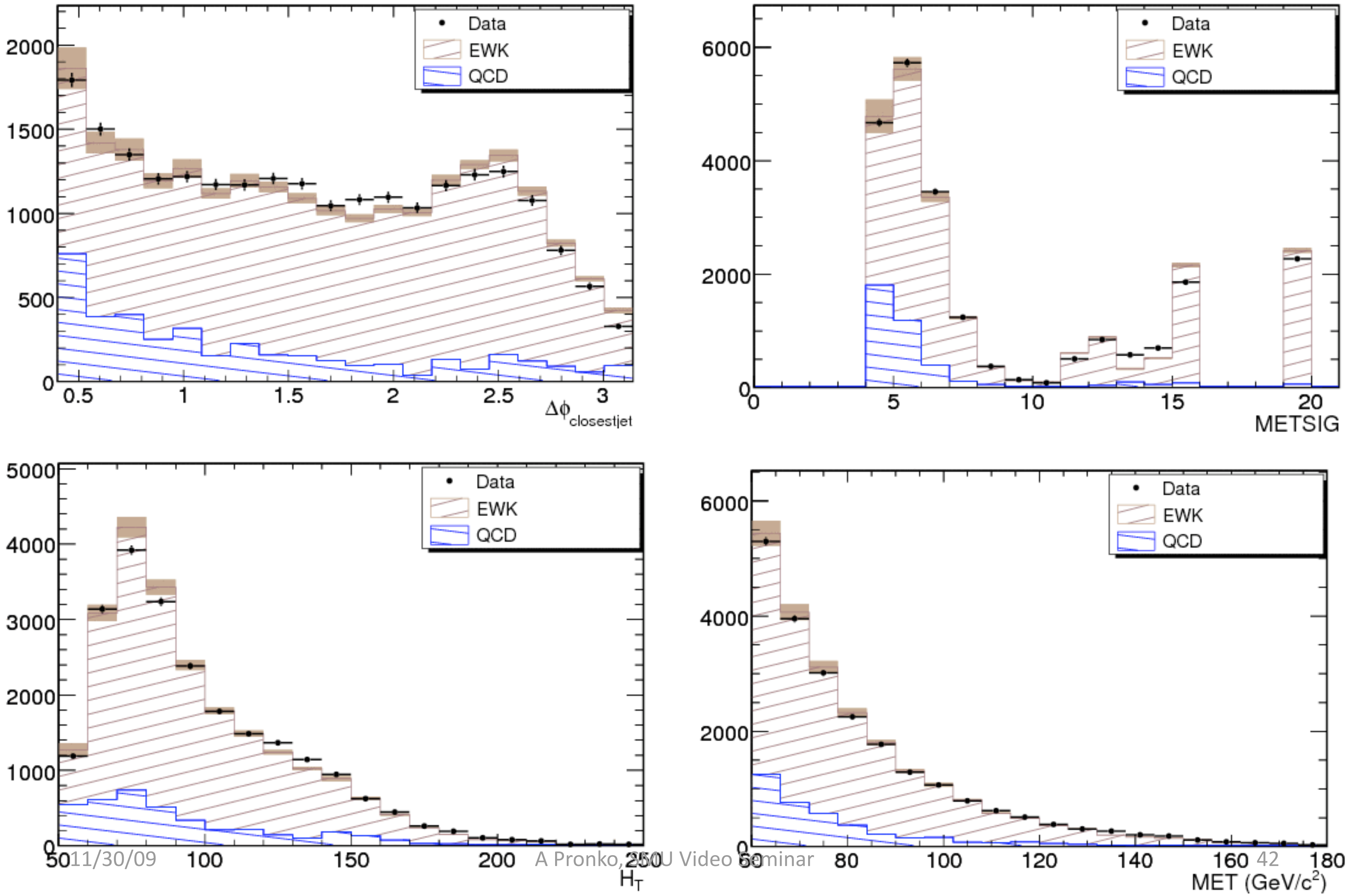




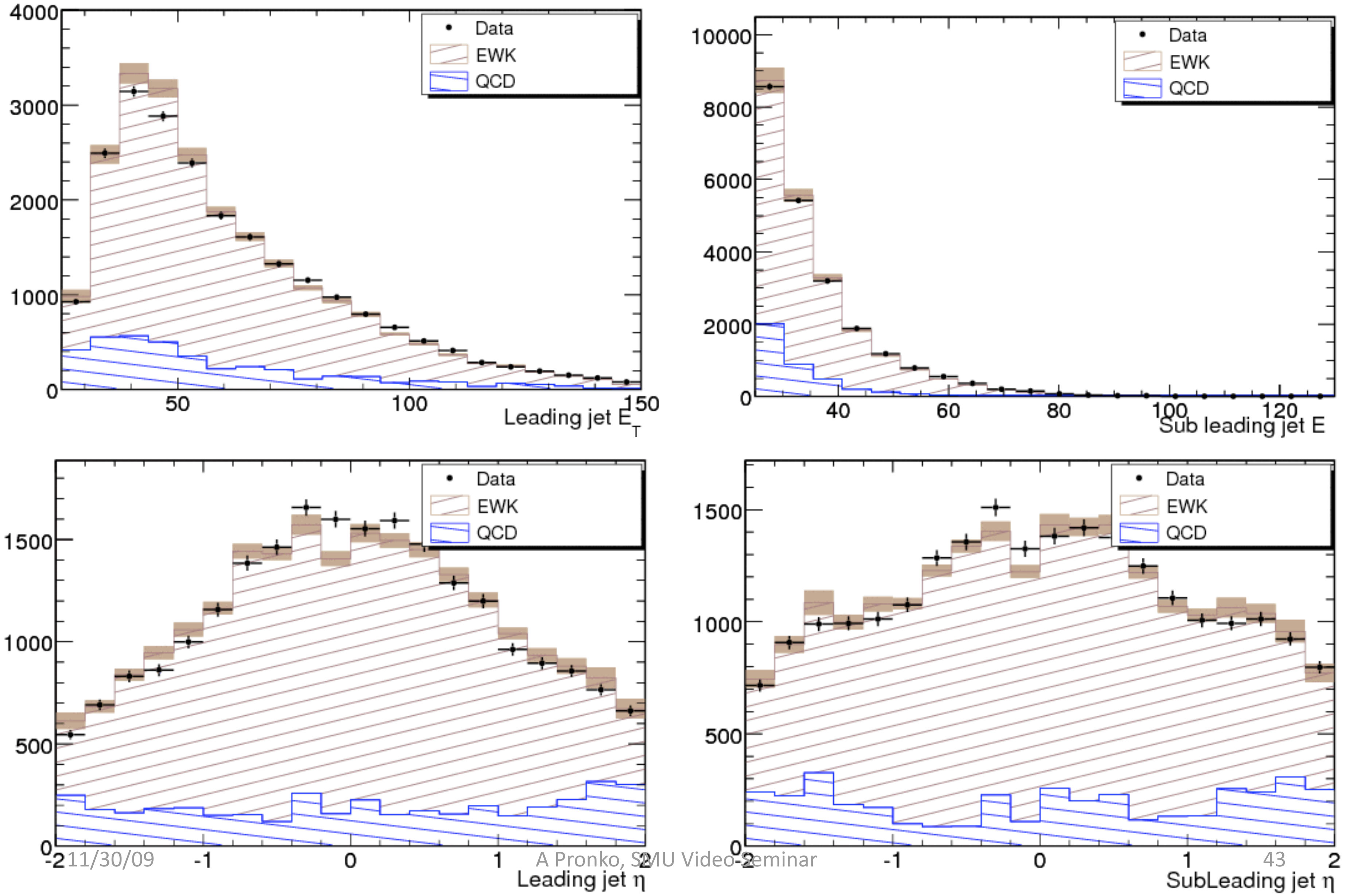


- JER uncertainty
  - Nvx=1 vs Nvx>1
  - Fit function
  - $\Delta\varphi_{jj}$ cut
  - E_T(jet3) cut

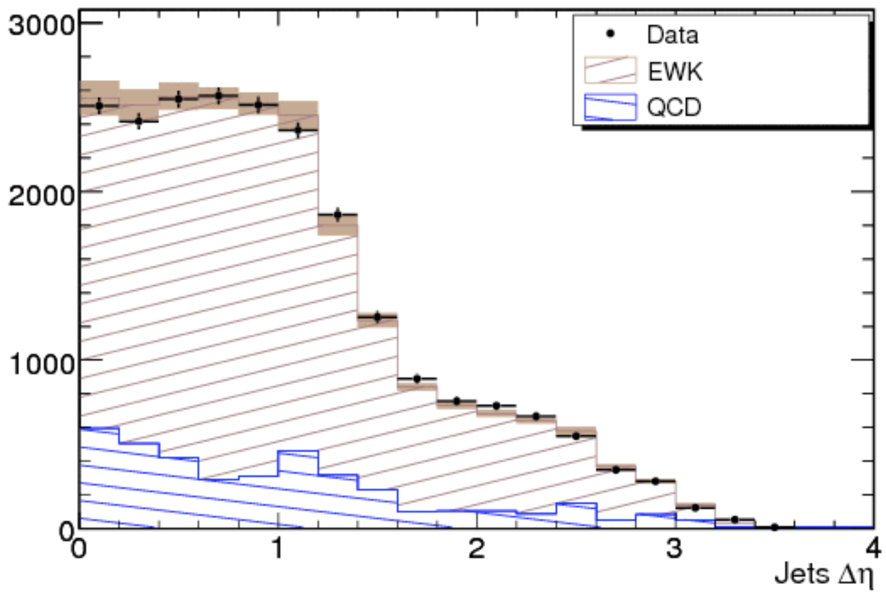
“Sideband” Kinematics: $40<M_{jj}<60$, $110<M_{jj}<160$

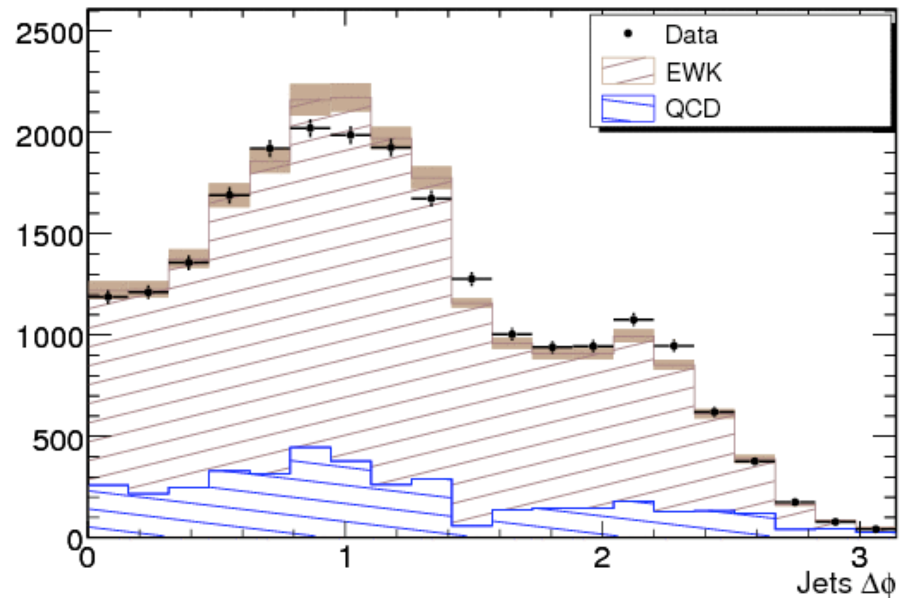


"Sideband" Kinematics: $40<M_{jj}<60$, $110<M_{jj}<160$

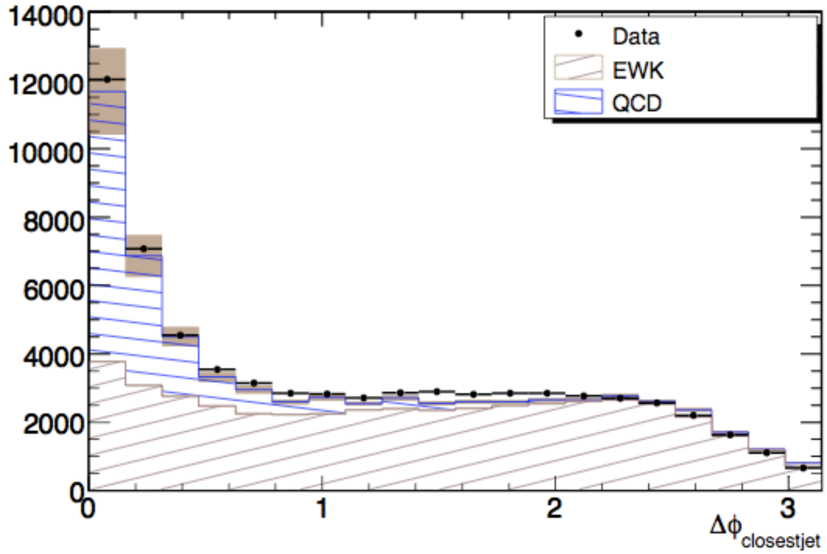


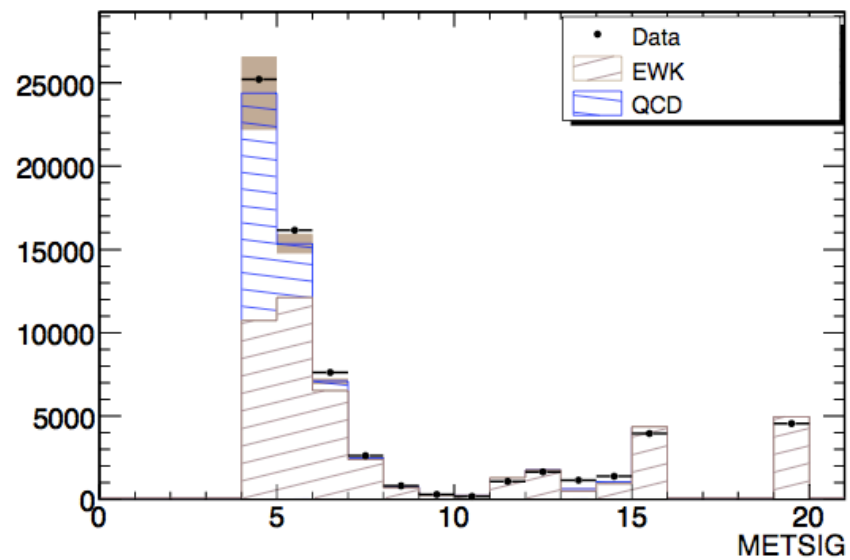
"Sideband" Kinematics: $40<M_{jj}<60$, $110<M_{jj}<160$

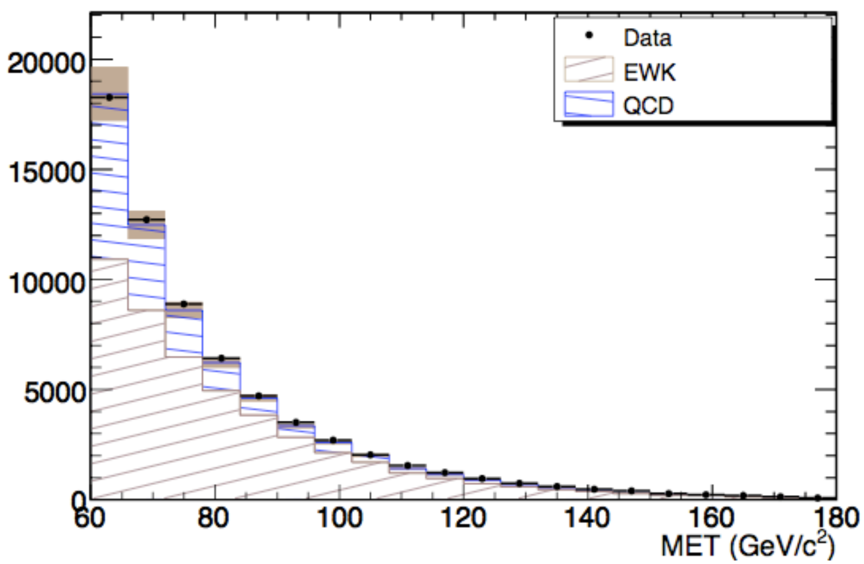


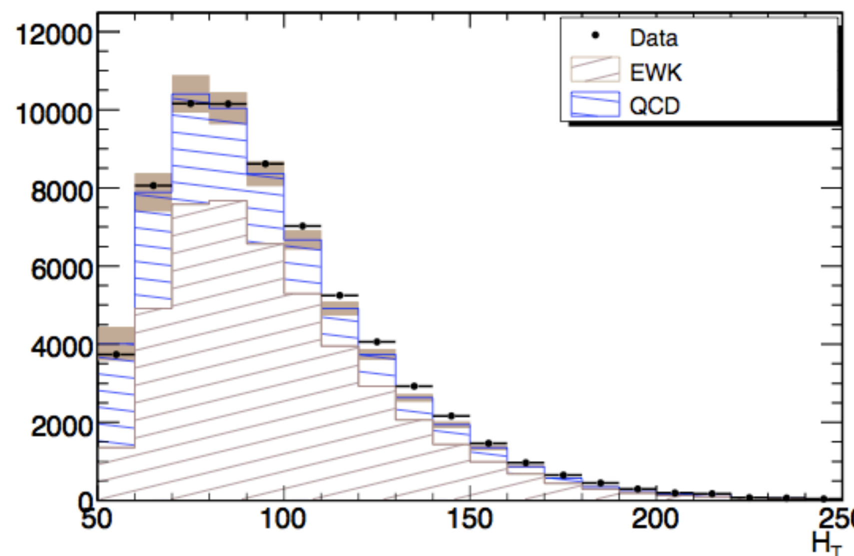


No $\Delta\varphi_{closest}$ Cut

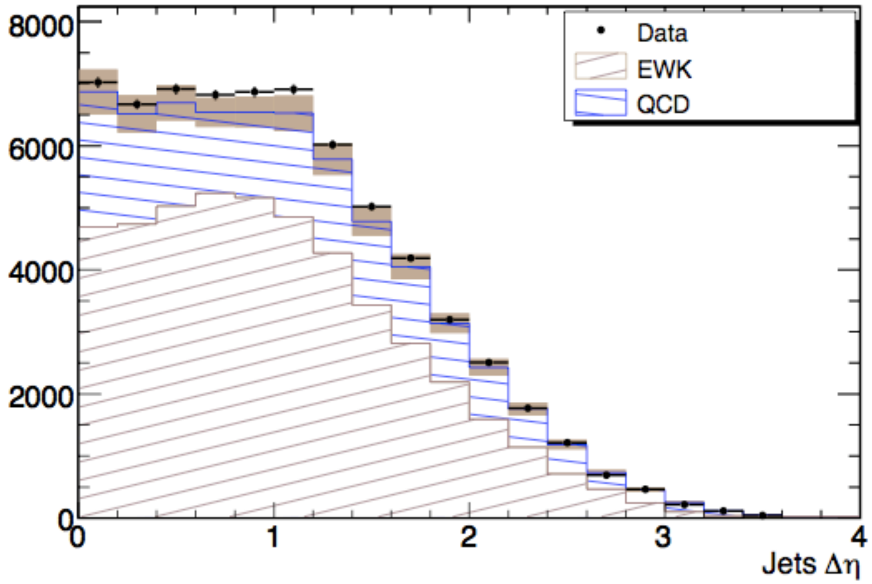


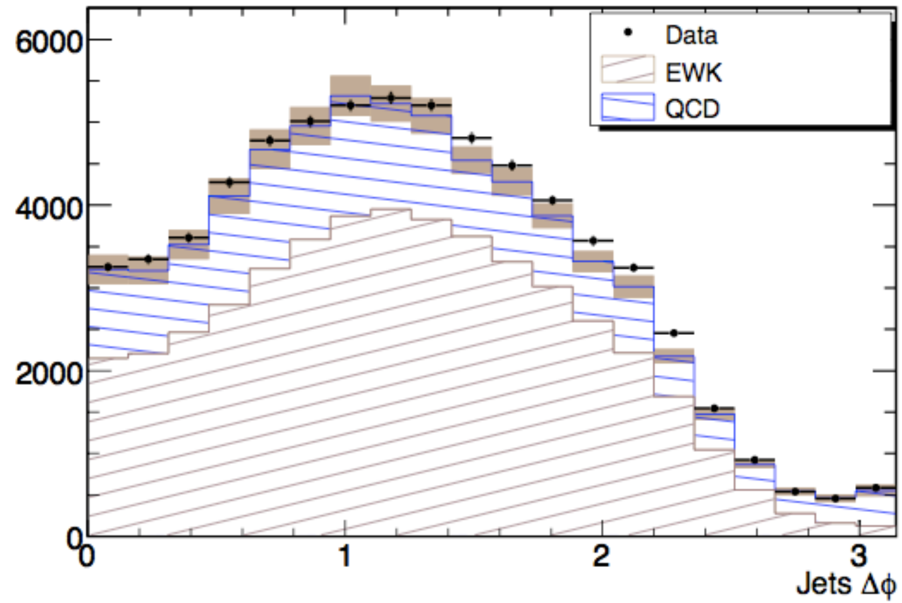






No $\Delta\varphi_{closest}$ Cut





Significance Part-I

- MINUIT reports 1516/239=6.34σ
  - PEs (s+b fit to s+b generated) imply a 6.45σ
  - -2*ΔL=LogL(s+b)-LogL(b)=42
    - TMath::Prob(42,1) = $9.1\times10^{-11} \rightarrow 6.48\sigma$
- Naïve approach:
  - $stat^2+syst^2=234^2+144^2=275^2$
  - $1516/275 = 5.5\sigma \rightarrow 3.8\times10^{-8}$

Significance Part-II

- Try to estimate the degradation of all systematic uncert. on the significance
  - Fix all parameters except N_{ewk} and N_{sig}
    - $\Delta L = 22 \rightarrow$ TMath::Prob(44,1)=$3.3\times10^{-11} \rightarrow >6\sigma$
  - Use alternative JER and repeat:
    - $\Delta L = 22 \rightarrow$ TMath::Prob(44,1)=$3.3\times10^{-11} \rightarrow >6\sigma$
  - Use alternative γ+jets and repeat:
    - $\Delta L = 14 \rightarrow$ TMath::Prob(28,1)=$1.2\times10^{-7} \rightarrow 5.3\sigma$
- The smallest significance corresponds to 5.3σ
  - Good agreement with Naïve approach: 5.5σ