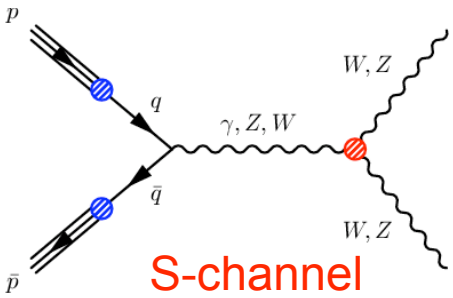
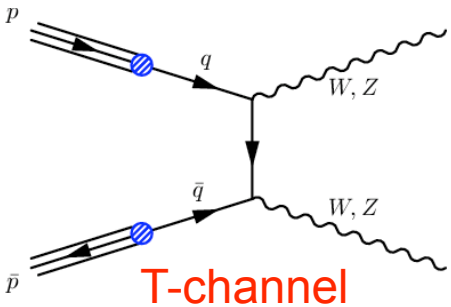
Diboson Production at the Tevatron

Sasha Pranko
Fermilab
(for CDF & D0 Collaborations)

Physics with Dibosons

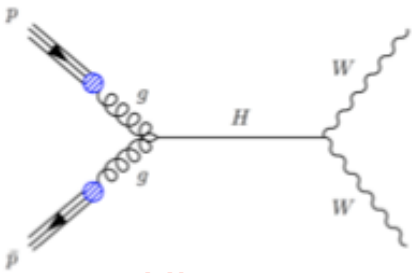


S-channel

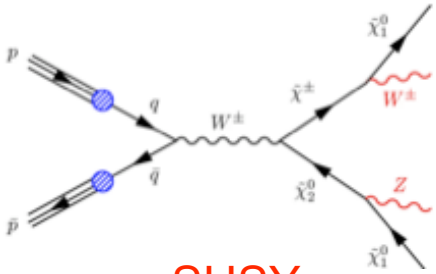


T-channel

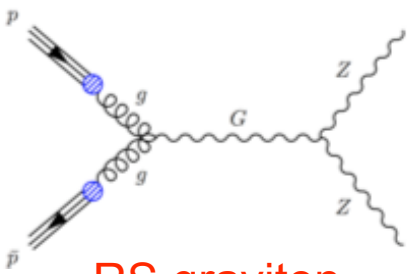
- Self-interactions of electroweak bosons are completely defined by $SU(2)_L \otimes U(1)_Y$ gauge symmetry
  - S-channel probes triple gauge couplings (TGC)
    - TGC depend on Q^2
    - Tevatron still has access to largest Q^2
  - X-sections can be enhanced by new physics



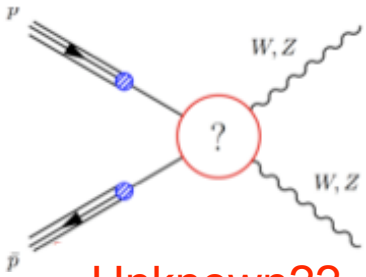
Higgs



SUSY

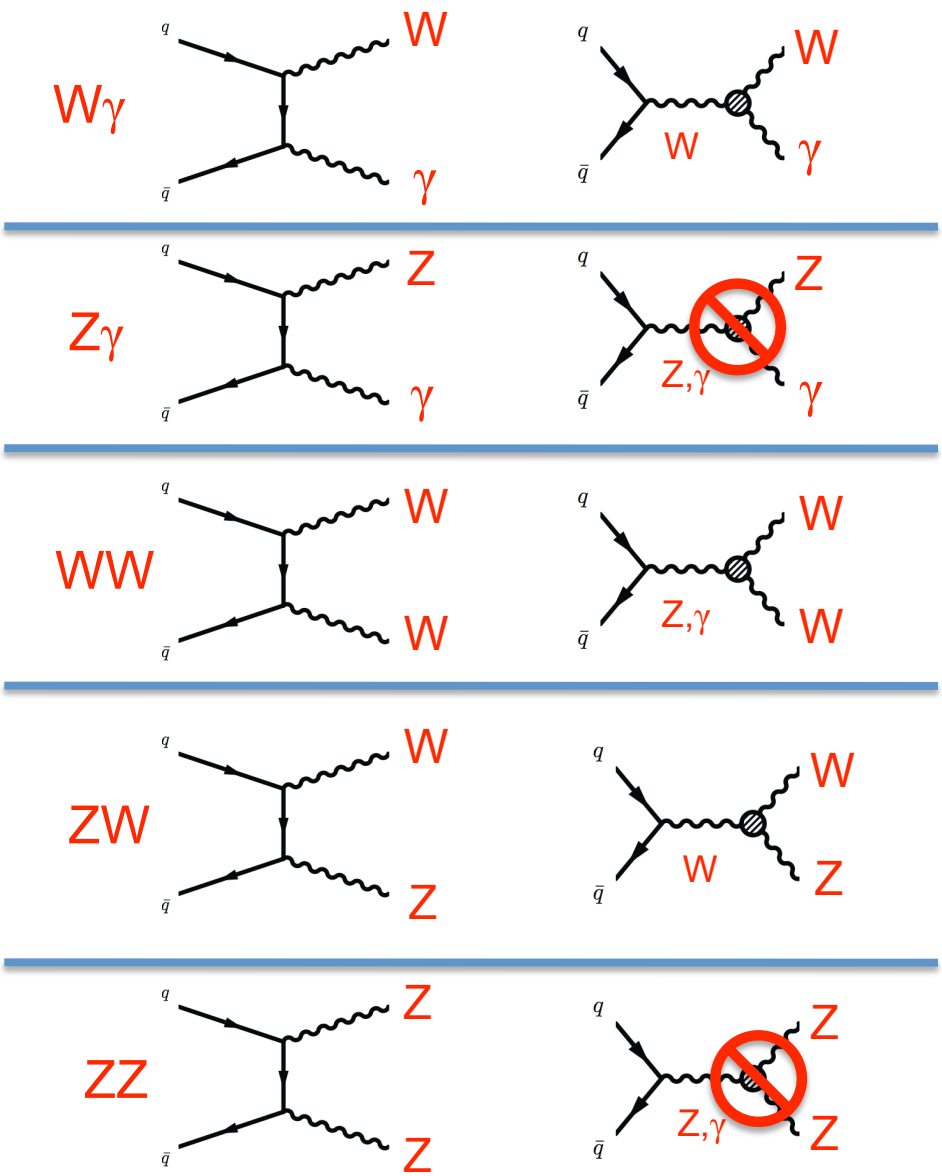


RS graviton

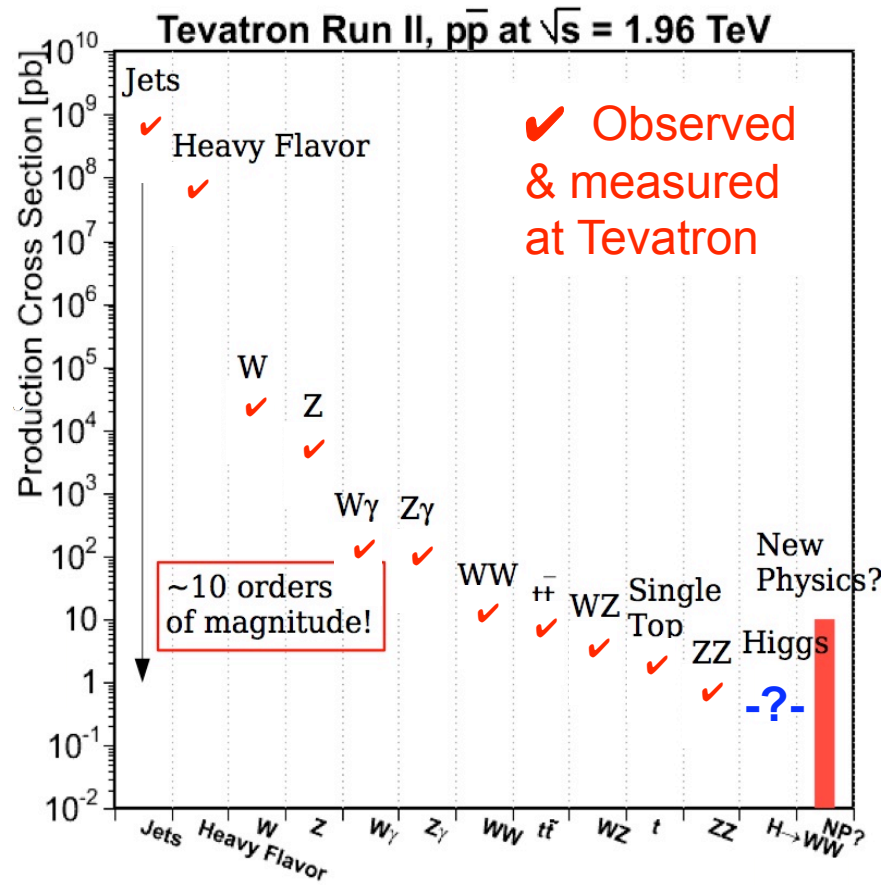


Unknown??

Diboson Processes at Tevatron



- Cross-sections & final states are similar to Higgs & New Physics

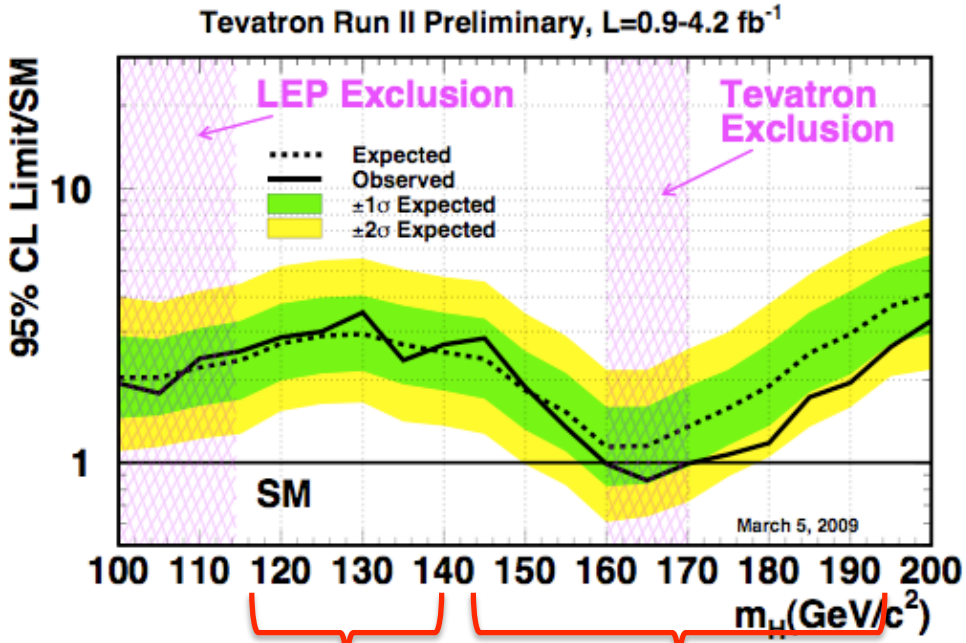


Road to Higgs is Paved with Dibosons

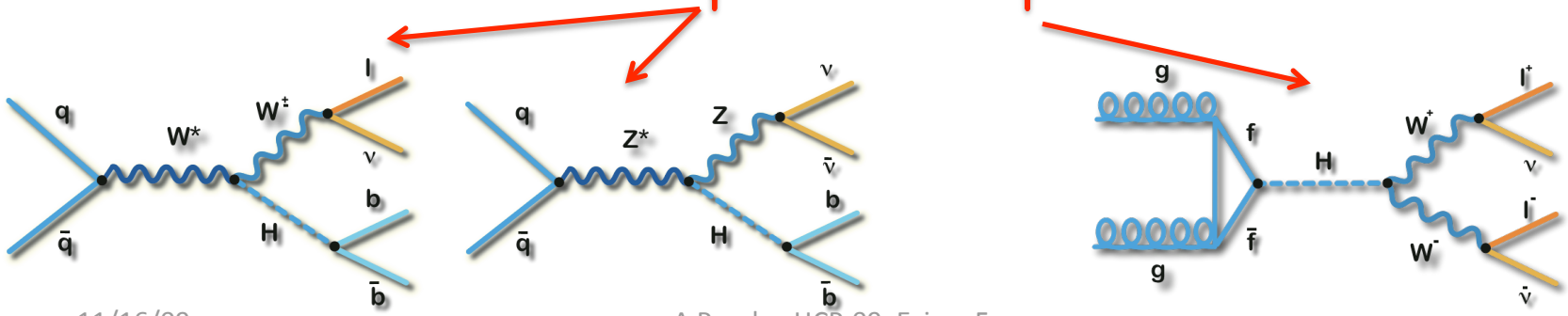
- Dibosons need to be well measured and understood before exclusion or observation of Higgs can be claimed

WH→lν+bb
similar to
WW+WZ→lν+jj

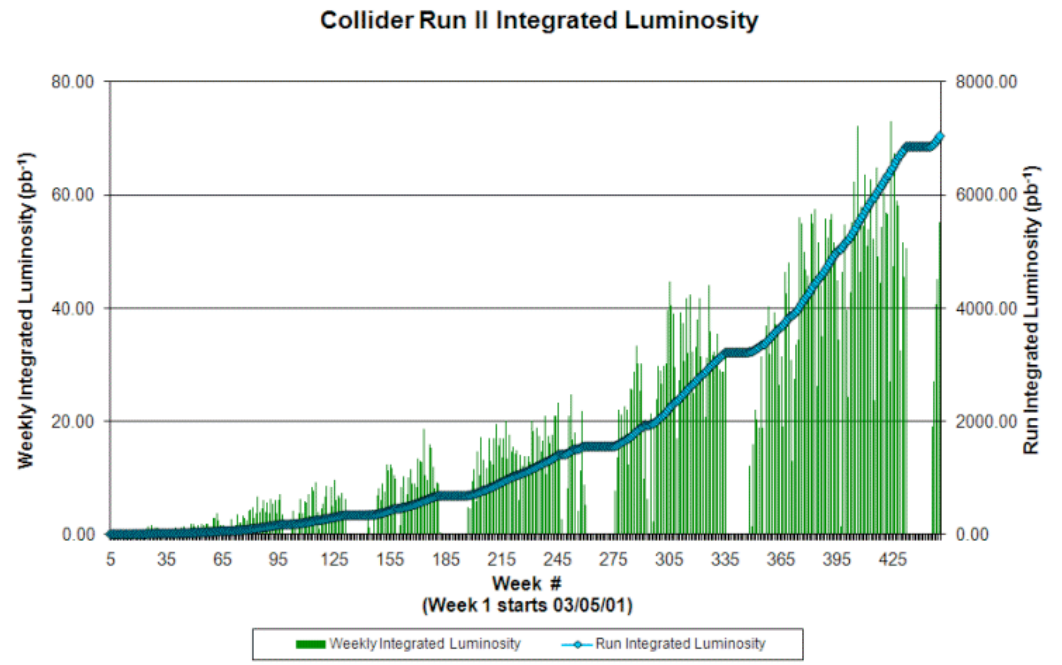
ZH→νν+bb
similar to
WZ+ZZ→νν+jj



Direct **WW→lν+lν** dominant background for **H→WW→lν+lν**



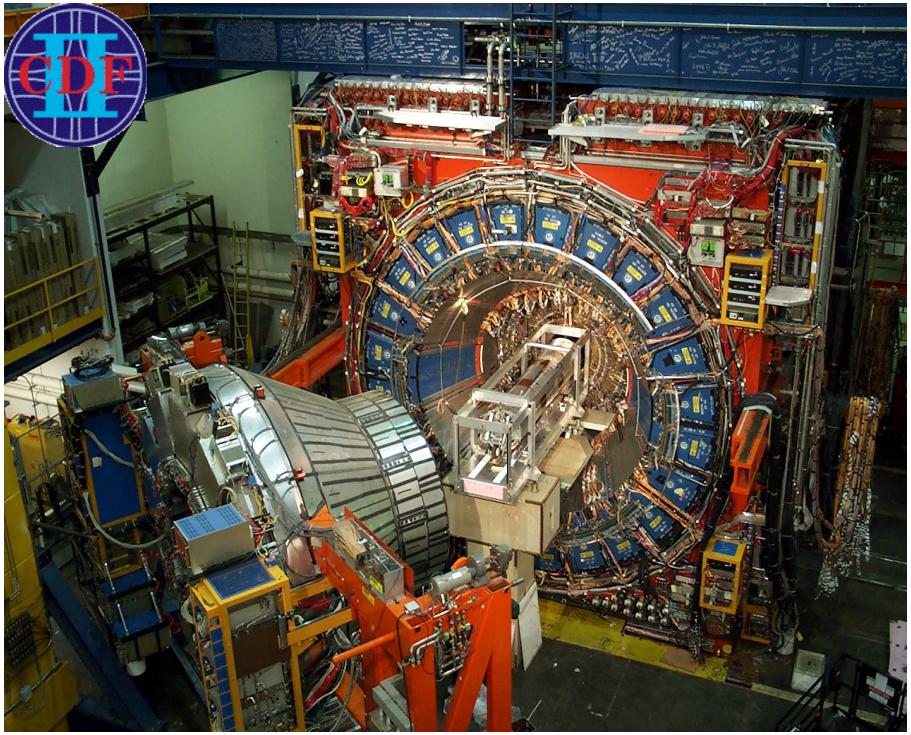
Tevatron is Running Very Well!



Process	Events in 1 fb^{-1}
$WW \rightarrow l\nu l\nu$	523
$ZW \rightarrow ll + l\nu$	111
$ZZ \rightarrow ll + ll$	~7
$WW \rightarrow jjl\nu$	5,100
$WZ \rightarrow jjl\nu + jj\nu\nu$	1,300
$ZZ \rightarrow \nu\nu jj$	420
$H_{160} \rightarrow WW \rightarrow l\nu l\nu$??	22
$WH_{120} \rightarrow l\nu + bb$??	22
$ZH_{120} \rightarrow \nu\nu + bb$??	13

- ~7 fb^{-1} per experiment
  - ~1.9 fb^{-1} in FY09
  - 55-60 pb^{-1} per week in FY09
- Ramping up speed after shutdown
  - Already 270 pb^{-1} since 09/15
- Running in 2011? Expect 10-12 fb^{-1} per experiment

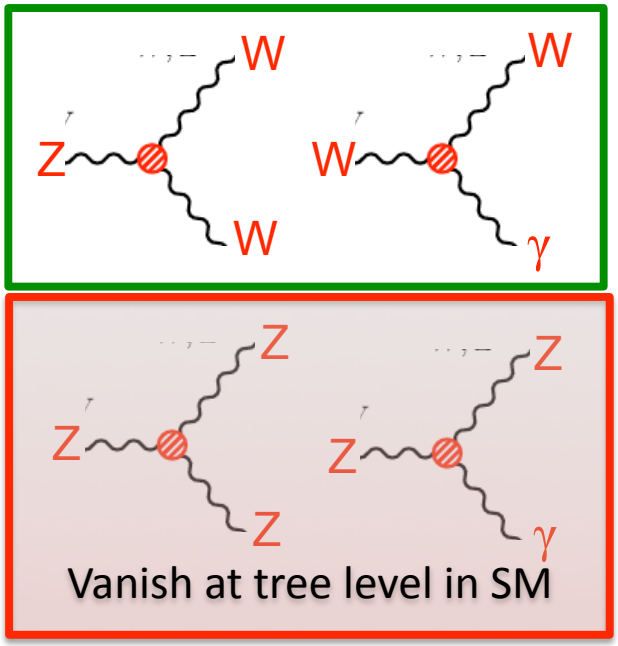
CDF and DØ Experiments



- Multipurpose detectors — classic design
  - “silicon”, central tracker, solenoid, calorimeter, muon chambers
- Operating well: 80-90% efficiency
- Broad physics program
  - QCD, EWK, top, B-physics, Higgs searches, searches for new physics

Triple Gauge Couplings (TGC)

- Sensitive to new physics
  - low-energy manifestation of new physics from higher mass scale
  - Direct production of new particles



$$\frac{\mathcal{L}_{\rm eff}^{VWW}}{g_{VWW}} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) + g_5^V\epsilon^{\mu\nu\lambda\rho}(W^*_\mu\partial_\lambda W_\nu - \partial_\lambda W^\dagger_\mu W_\nu)V_\rho + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu\tilde{V}^{\nu\lambda}$$

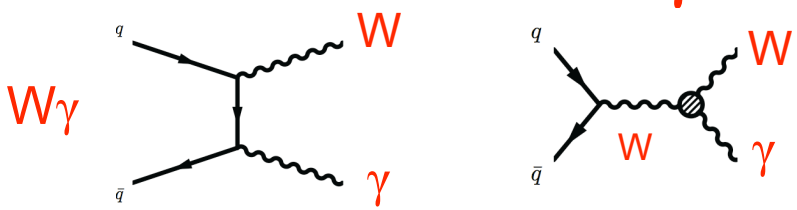
2×7 parameters at LO

- SM: all 0 except for $g_1^V=k_V=1$, V=Z, γ
- Respect CP, $SU(2)_L \otimes U(1)_Y$ and EM gauge invariance
  - 3 free parameters: $\Delta k_Z=\Delta g_1^Z-\Delta k_\gamma \tan^2\theta_W$ and $\lambda\equiv\lambda_Z=\lambda_\gamma$
- Assume equal couplings for ZWW & γWW respecting CP
  - 2 free parameters: $\Delta k\equiv\Delta k_Z=\Delta k_\gamma$ and $\lambda\equiv\lambda_Z=\lambda_\gamma$

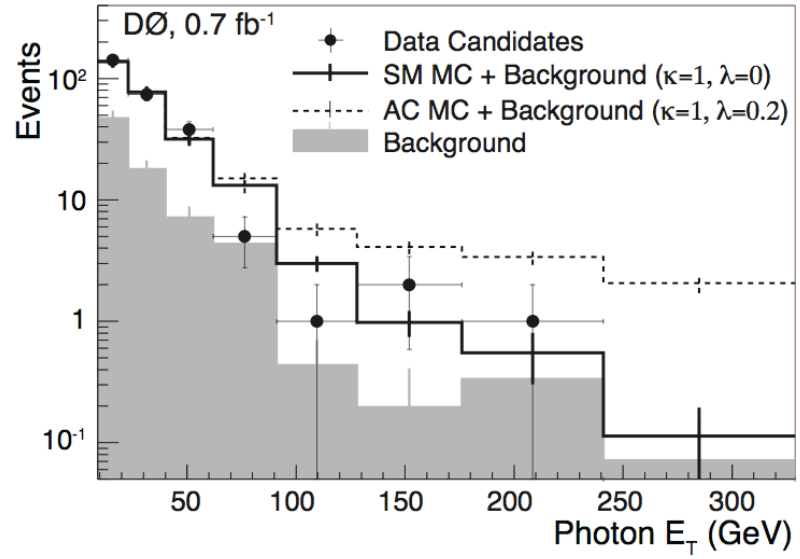
$$a(\hat{s}) = \frac{a_0}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}$$

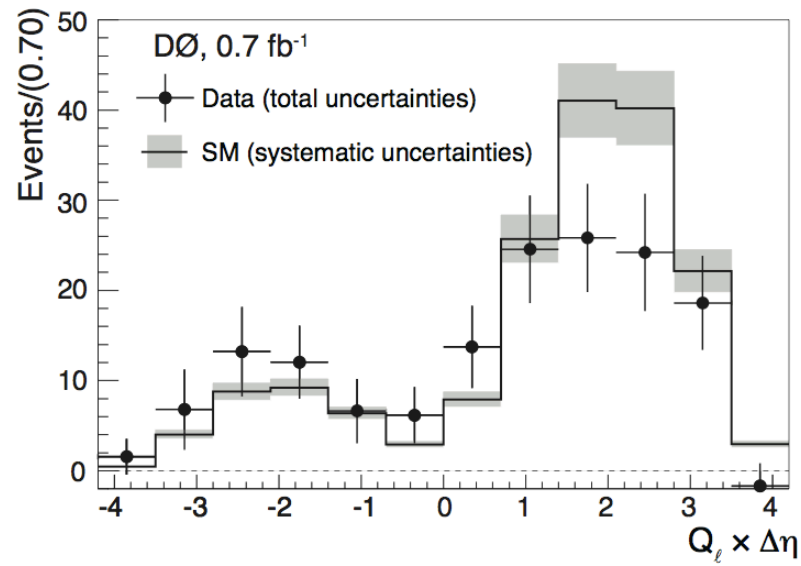
Λ=2 TeV

Wγ Production

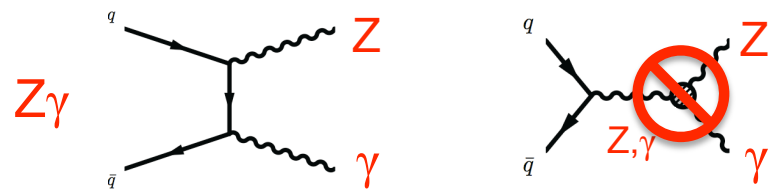


- Wγ→$l\nu$+γ production
  - Isolates WWγ coupling
  - Radiation-amplitude zero
    - Predicted in 1979; studied by D0 in 2008
- Selection
  - Lepton $E_T(P_T)$, MET>20 GeV, $E_T(\gamma)$>9 GeV
  - FSR veto: M_{T3}>120 GeV/c^2
- Results
  - 95% CL on aTCG: $0.49<k_\gamma<1.51$, $-0.12<\lambda_\gamma<0.13$
    - PRL 100, 241805 (2008)
  - σ=14.8±1.6 (stat)±1.0 (syst)±1.0 (lum) pb
    - For $E_T(\gamma)$>8 GeV, $\Delta R(\gamma\text{-}l)$>0.7
    - NLO theory: 16.0±0.4 pb Phys.Rev.D71:091108,2005

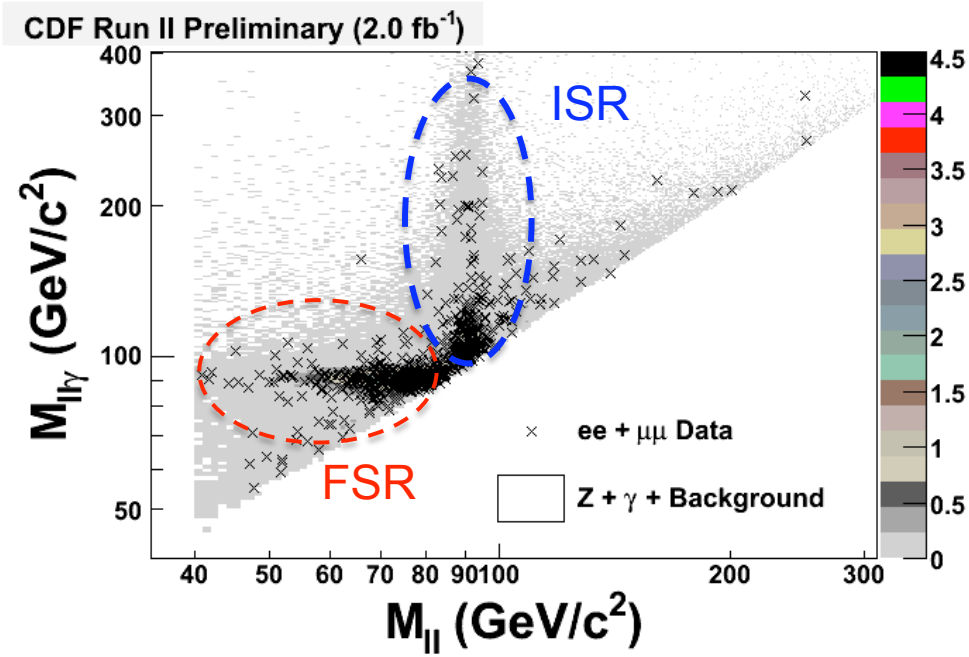


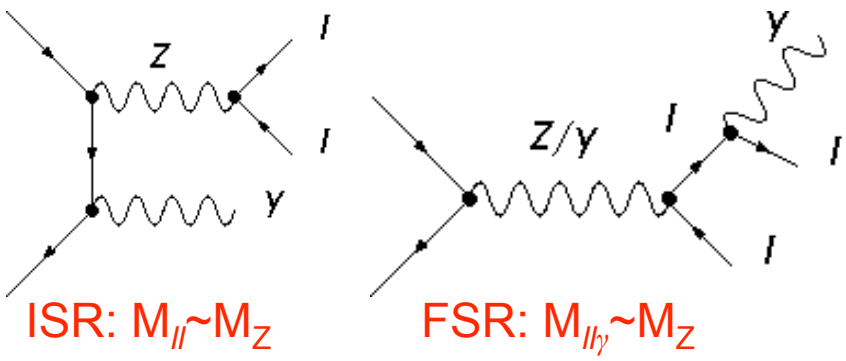


Zγ Production



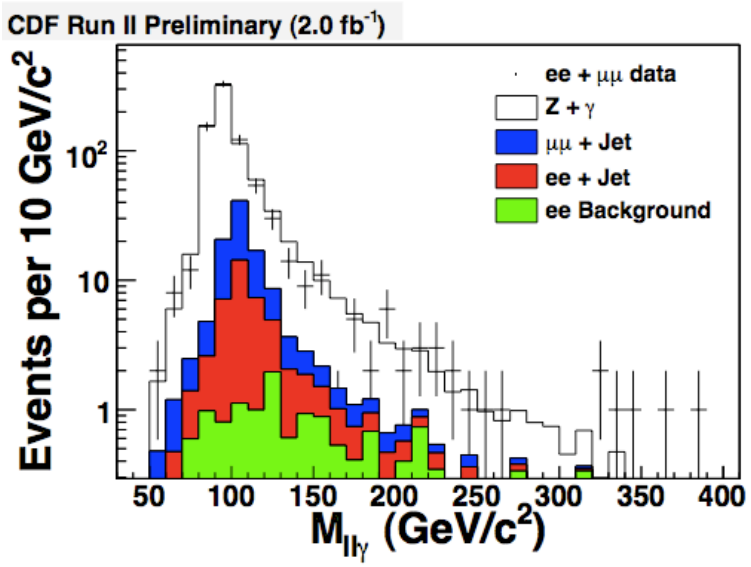
- Zγ production, Z→*ee*/μμ
  - SM: photon FSR out of *ee*/μμ
  - SM: photon ISR out of quark
  - Can be enhanced by new physics or Higgs
    - E.g., fermiophobic H→Zγ
- 2 fb^{-1} of μ-data, 1.1 fb^{-1} of e-data
  - Lepton: $E_T(P_T)$>20 GeV, M_{ll}>40 GeV/c^2
    - Central (|η|<1.1), forward (|η|<2.8)
  - Photon: central, E_T>7 GeV, $\Delta R_{\gamma l}$>0.7

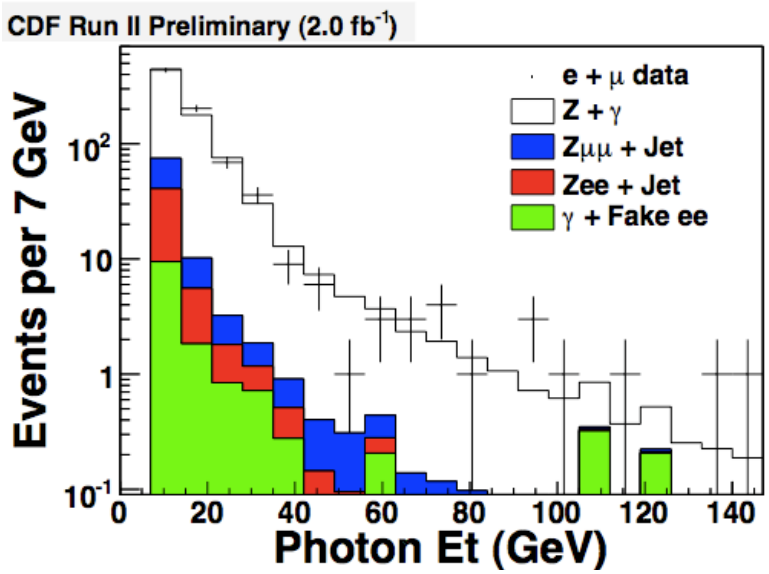




ISR: M_{ll}~M_Z FSR: $M_{ll\gamma}$~M_Z

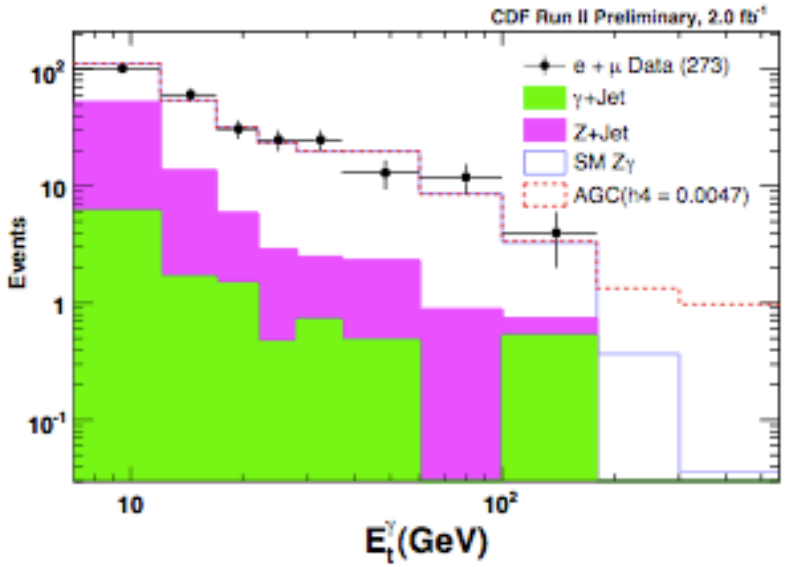
Zγ Production Cross Section

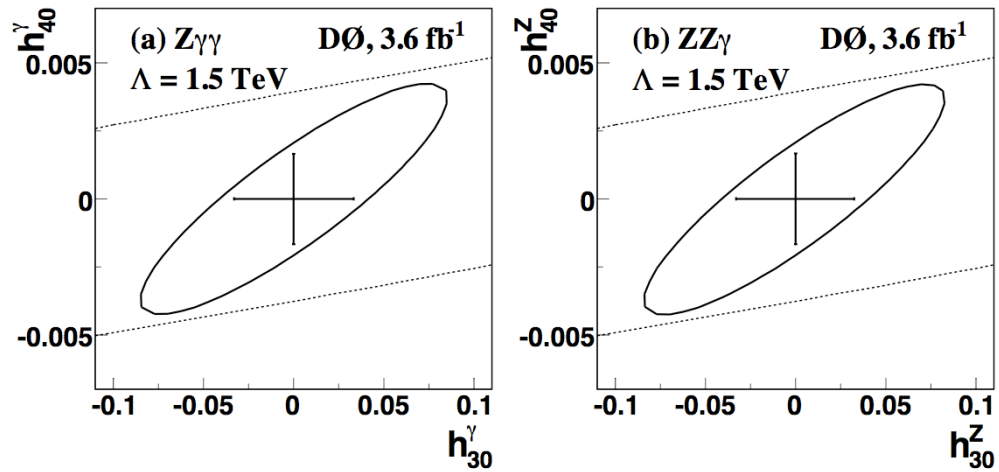




- Results
  - CDF: 4.6 ± 0.2 (stat) ± 0.3 (syst) ± 0.3 (lum) pb
    - CDF ISR region ($M_{ll\gamma}$>100 GeV/c^2): 1.2 ± 0.1 (stat) ± 0.2 (syst) ± 0.1 (lum)
  - NLO theory: 4.5 ± 0.4 pb
    - NLO theory ISR region: 1.21 ± 0.10 pb
- Dominant background: Z+jets (~12%)
- Uncertainties: photon background (3.5%), acceptance (4.0%)

Limits on Anomalous Zγγ & ZZγ TGC



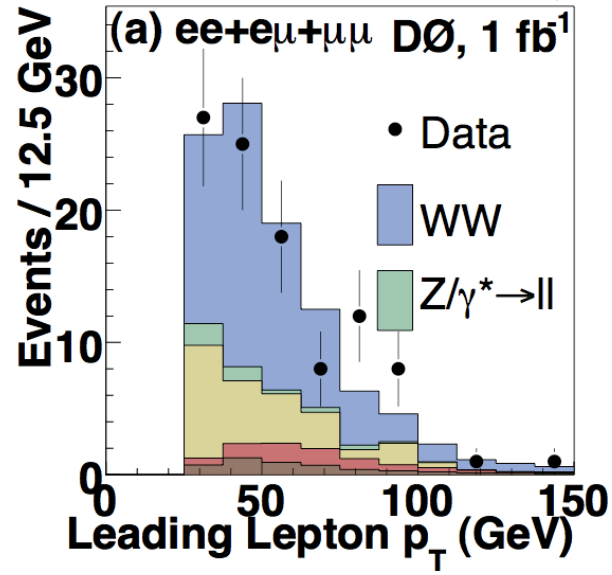


- CDF: Z(*ll*)+γ and Z(νν)+γ data
  - Z(νν)+γ : 2 fb^{-1}, $E_T(\gamma)$>90 GeV; MET>50 GeV, jet & track veto
- D0: Z(νν)+γ data
  - 3.6 fb^{-1}, $E_T(\gamma)$>90 GeV; MET>70 GeV, jet & track veto
  - PRL 102, 201802 (2009)

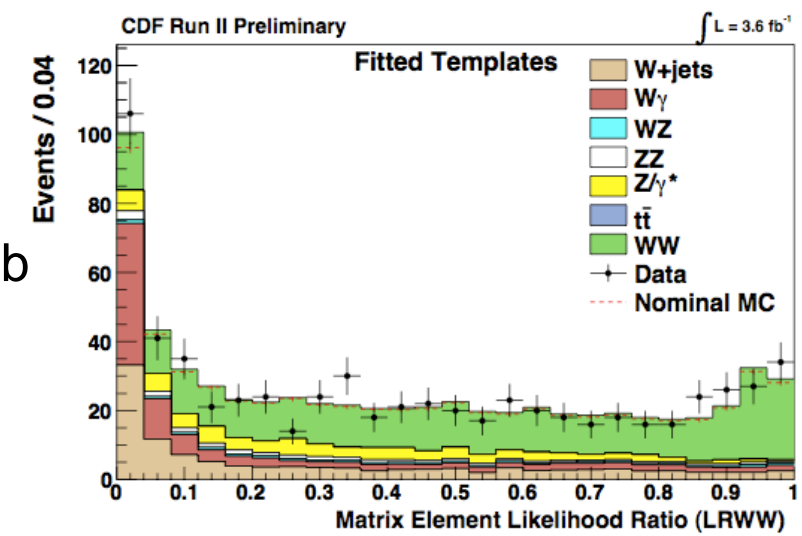
	CDF	D0	LEP-II
$\lvert h^Z_3 \rvert$	<0.050	<0.033	-0.2 : 0.07
$\lvert h^Z_4 \rvert$	<0.0034	<0.0017	-0.05 : 0.12
$\lvert h^\gamma_3 \rvert$	<0.051	<0.033	-0.049 : 0.008
$\lvert h^\gamma_4 \rvert$	<0.0034	<0.0017	-0.02 : 0.034

Parameterization from G.J. Gounaris *et al.* PRD 62, 073012.

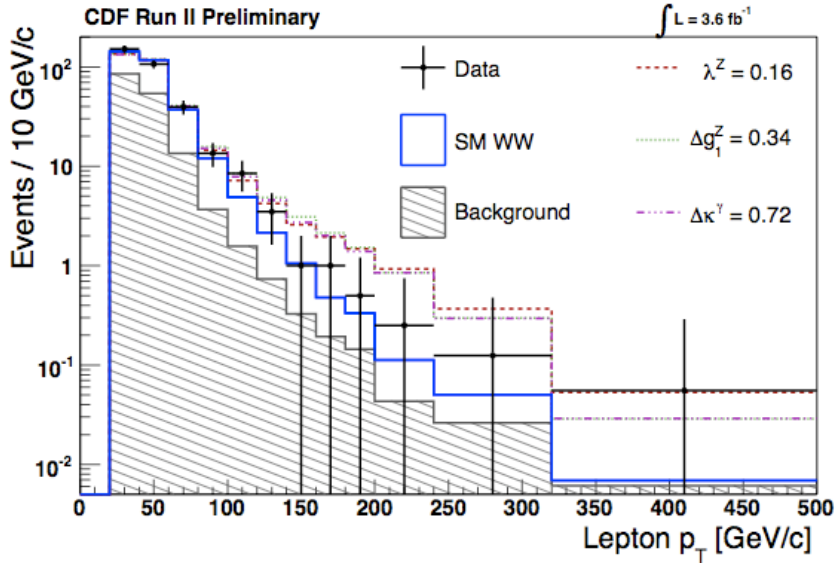
WW Production



- WW→lν+lν production
  - Test SM predictions: x-section, TGC
    - Dominant background for H→WW
    - Same analysis techniques as in H→WW
  - Can be enhanced by new physics or Higgs
  - Look for anomalous TGC
- Results
  - CDF: 12.1 ± 0.9 (stat) $^{+1.6}_{-1.4}$ (syst) pb
  - D0: 11.5 ± 2.1 (stat+syst) ± 0.7 (lum) pb
    - PRL 103, 191801 (2009)
  - NLO theory: 11.66 ± 0.70 pb



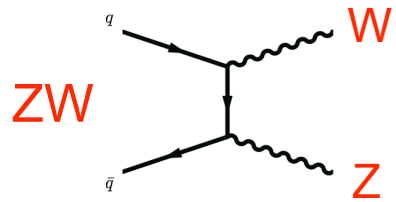
Limits on Anomalous ZWW & γWW TGC

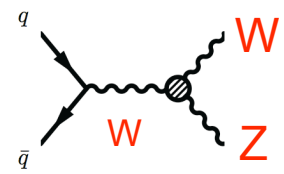


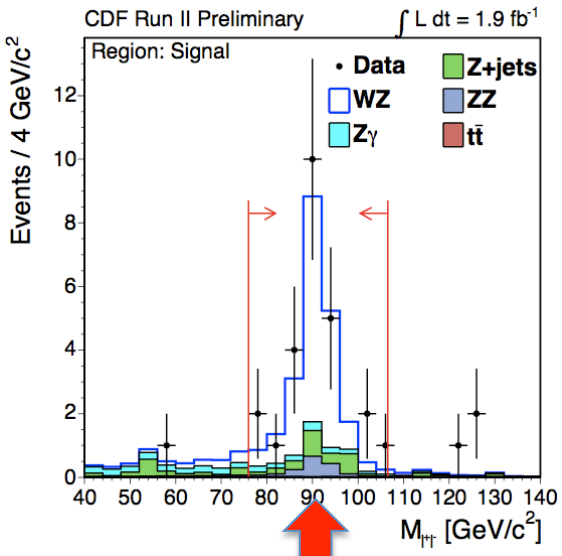
CDF Preliminary Results at 3.6fb^{-1}			
Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	(-0.14,0.15)	(-0.22,0.30)	(-0.57,0.65)
1.5TeV	(-0.16,0.16)	(-0.24,0.34)	(-0.63,0.72)

D0 Results with 1 fb^{-1}			
2.0 TeV	-0.16, 0.18	-0.14, 0.30	-0.54, 0.83
ZWW =γWW	same	N/A	-0.12, 0.35

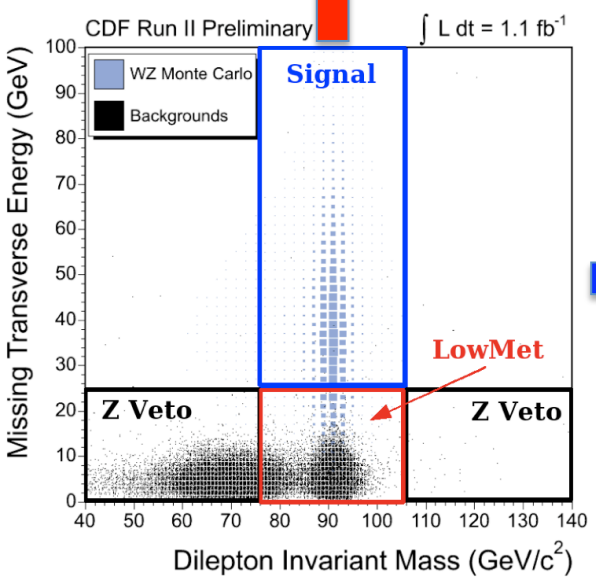
WZ Production

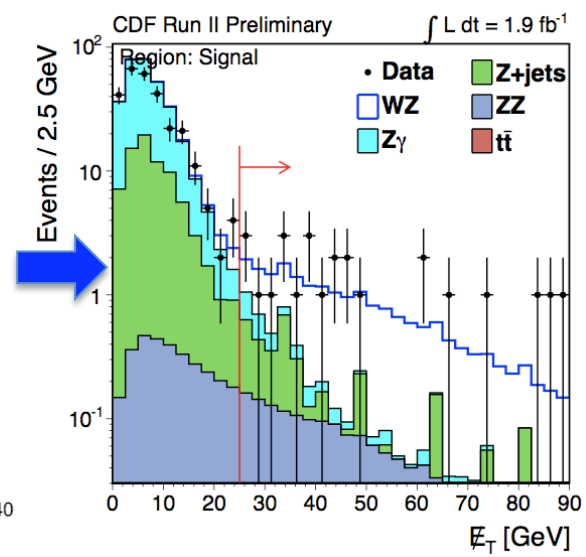






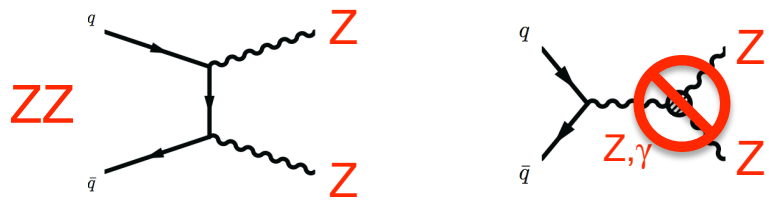
- WZ state is unique to Tevatron
  - Not produced at LEP
  - Isolates WWZ coupling
- Analysis with 1.9 fb^{-1}
  - One energetic lepton plus Z-boson (l^+l^- pair)
  - Large MET
  - CDF: $4.3\ ^{+1.3}_{-1.0}$(stat) ± 0.2(syst) ± 0.3(lum) pb
  - NLO theory: 3.7 ± 0.3 pb

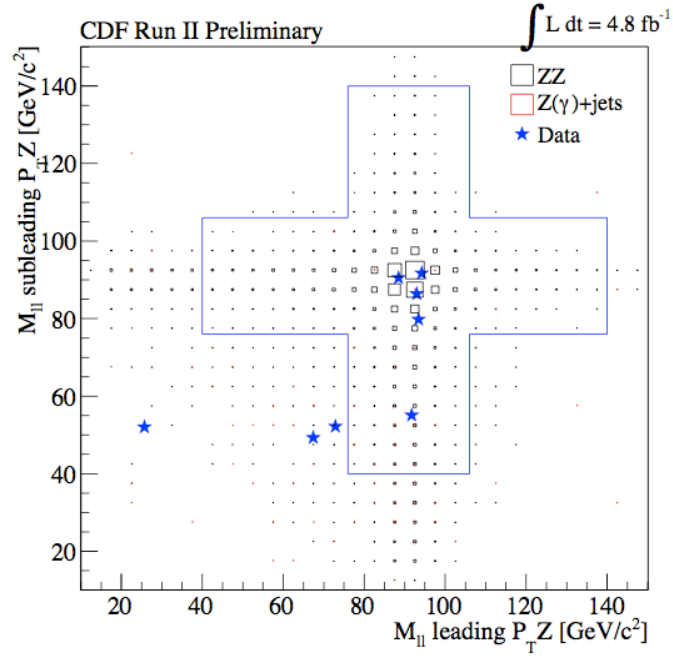




CDF 1.1 fb^{-1}: PRL 98,161801
D0 1.0 fb^{-1}: PRD 76, 111104

Observation of ZZ→*ll*+*ll* Production





- ZZ production
  - Smallest SM diboson x-section
  - Previously observed in llνν+llll mode
  - Can be enhanced by New Physics
    - e.g., RS gravitons
- Analysis with 4.8 fb^{-1}
  - Leading lepton $E_T(P_T)$>20 GeV
  - Sub-leading lepton $E_T(P_T)$>10 GeV
  - Min $\Delta R_{leptons}$>0.1
  - 76 GeV/c^2<M_{pair-1}<106 GeV/c^2
  - 40 GeV/c^2<M_{pair-2}<100 GeV/c^2
  - 5.7σ signal significance

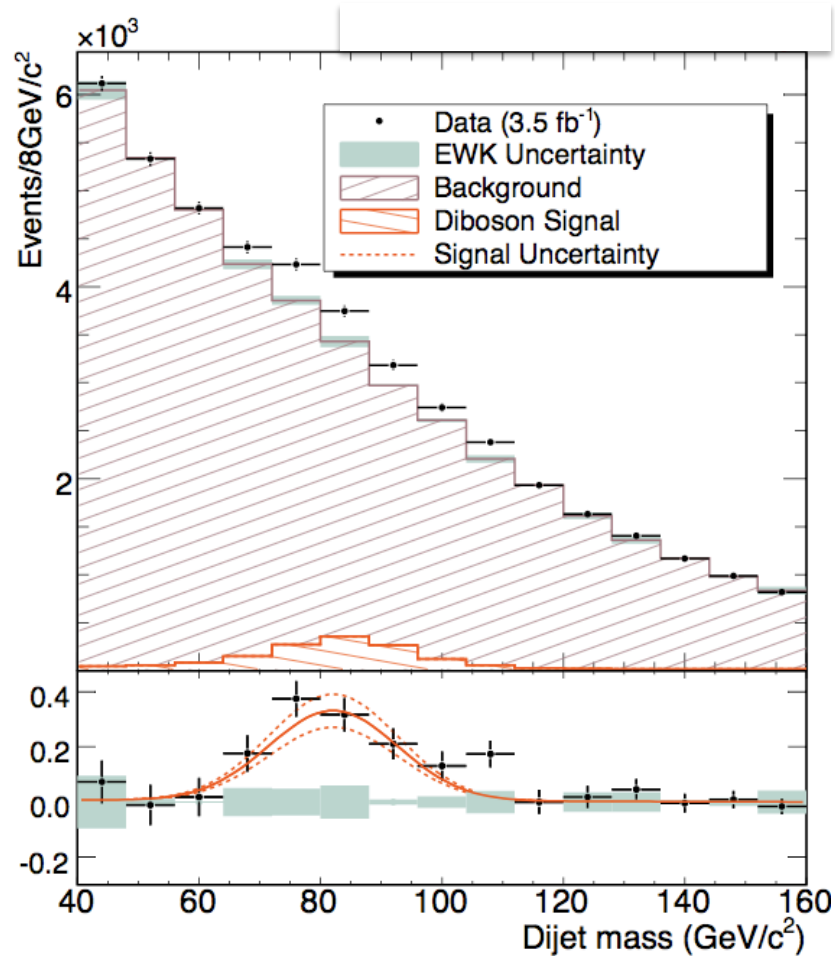
Events in $\mathcal{L} = 4.8$ fb^{-1}	
Signal	4.68 ± 0.02(stat.) ± 0.76(syst.)
Z(γ)+jets	0.041 ± 0.016(stat.) ± 0.029(syst.)
Total expected	4.72 ± 0.03(stat.) ± 0.76(syst.)
Observed	**5**

$$\sigma_{p\bar{p}\to ZZ} = 1.56^{+0.80}_{-0.63}(stat.) \pm 0.25(syst.) \quad pb$$

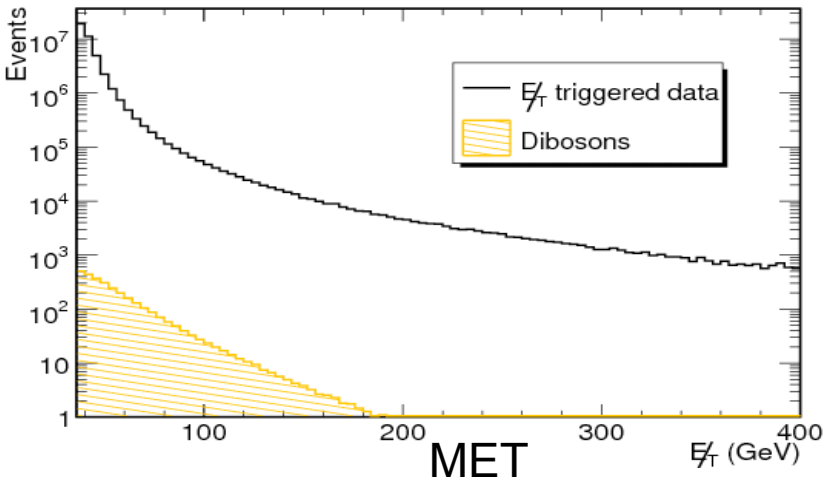
$$\sigma_{p\bar{p}\to ZZ-Th} = 1.4 \pm 0.1(stat. + syst.) \quad pb$$

First Observation of VV→MET+jj

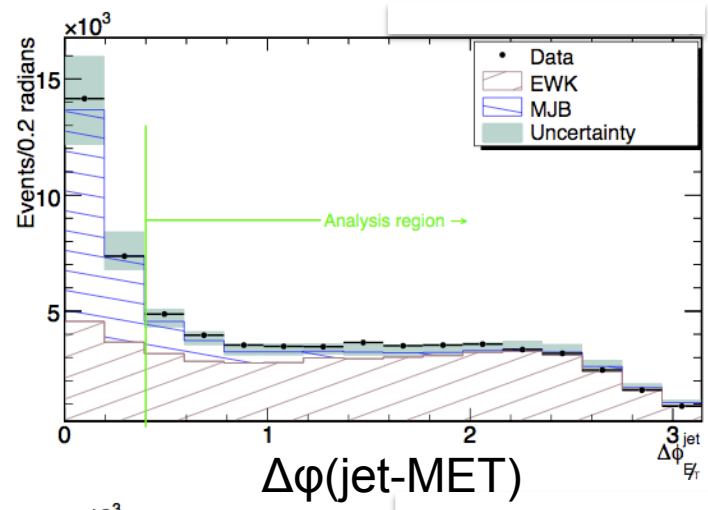
- VV→MET+jj final state
  - Sensitive to WW, WZ, ZZ
    - Can be enhanced by H→W*W
  - Milestone for low mass Higgs searches
    - Similar final state: ZH→νν+bb
    - Develop/Test analysis techniques
- Results in 3.5 fb^{-1}
  - Extracted signal:
    - 1516 ± 239(stat) ± 144(syst) events
    - 5.3σ signal significance
  - CDF: 18.0 ± 2.8(stat) ± 2.4(syst) ± 1.1(lum) pb
  - NLO theory: 16.8±0.5 pb
  - PRL 103, 091803 (2009)

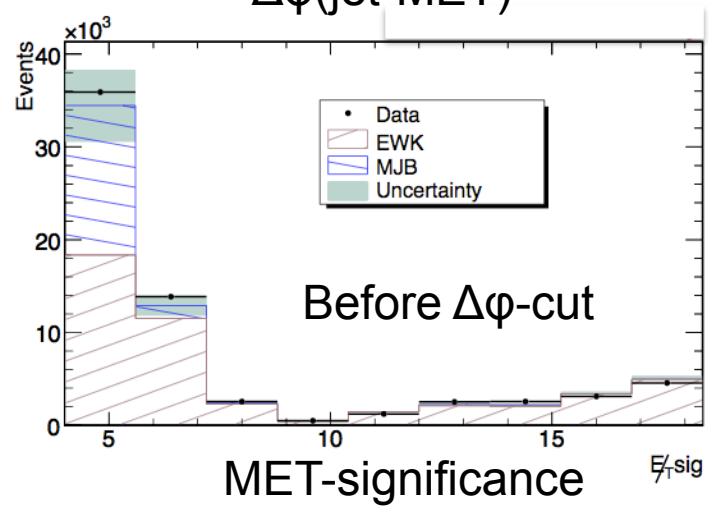


First Observation of VV→MET+jj



QCD rejection

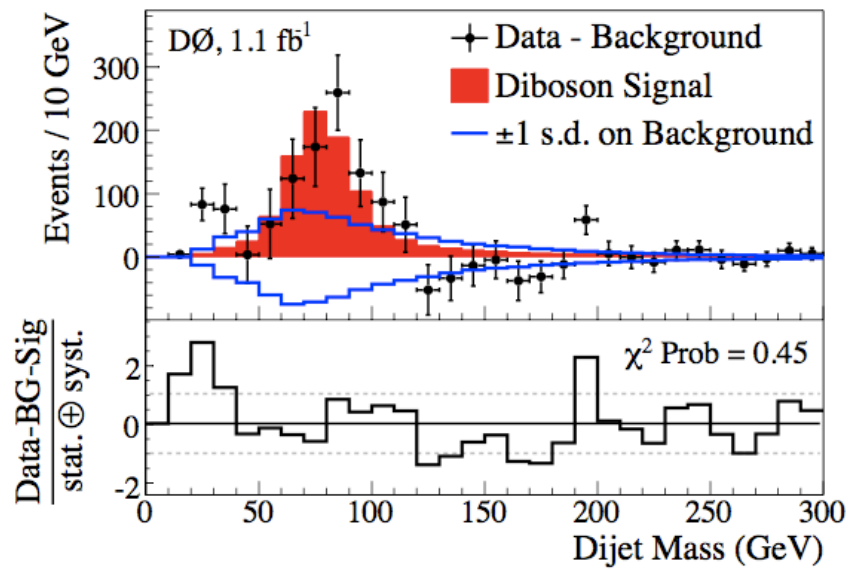


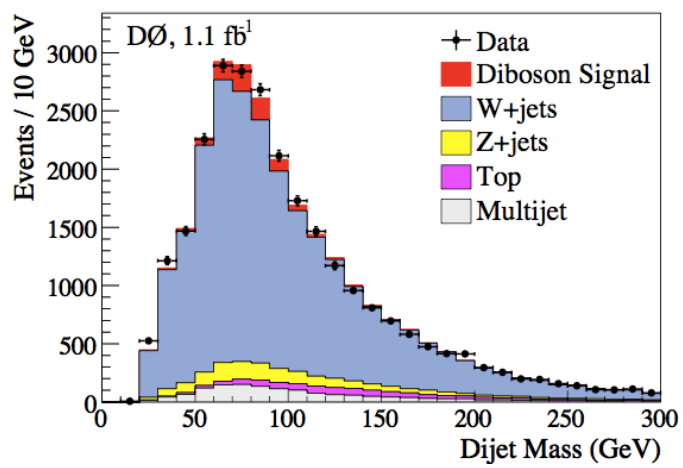


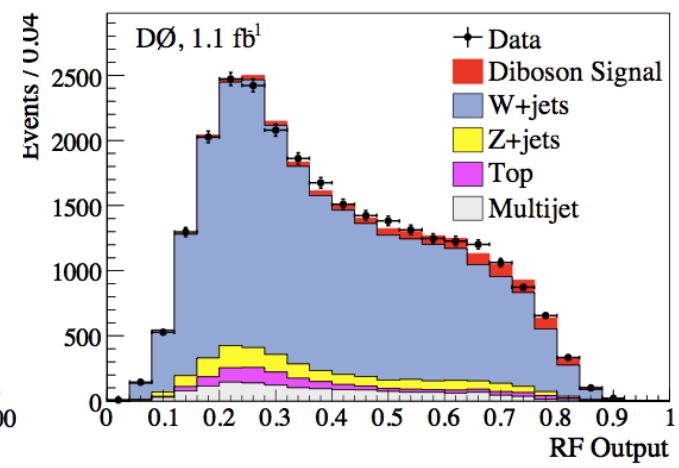
- Analysis challenge
  - Triggered data dominated by QCD multi-jet events with fake MET
    - After trigger: **Signal/QCD~10^{-4}**
  - Reject QCD based on sophisticated MET-resolution model
    - After QCD rejection: **Signal/QCD~0.2**
    - MET-resolution model: arXiv: 0910.5170

Evidence for WW+WZ→$l\nu$+jj

- WW+WZ→$l\nu$+jj channel
  - Similar to WH→$l\nu$+bb
  - Same analysis technique
    - Validate multivariate techniques to extract small signal in large background
- Results in 1.1 fb-1
  - 20.2±2.5(stat)±3.6(syst)±1.2(lum) pb
  - NLO theory: 16.1±0.9 pb
  - PRL 102, 161801

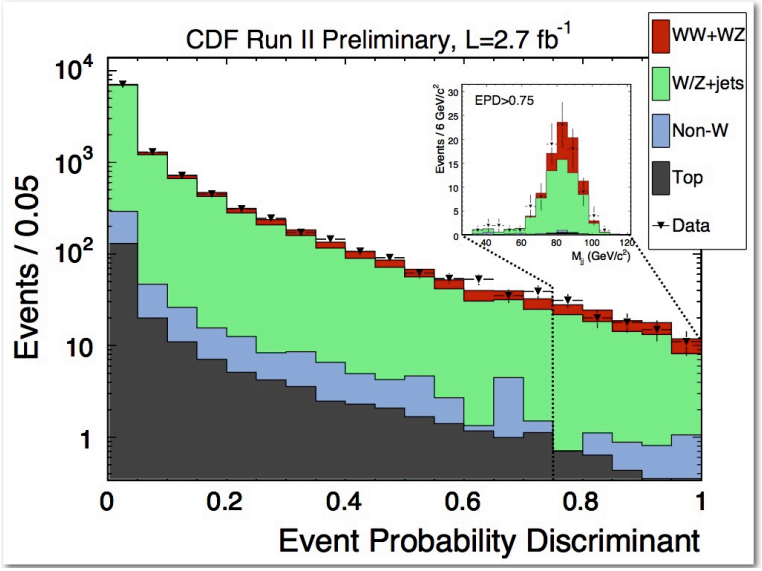


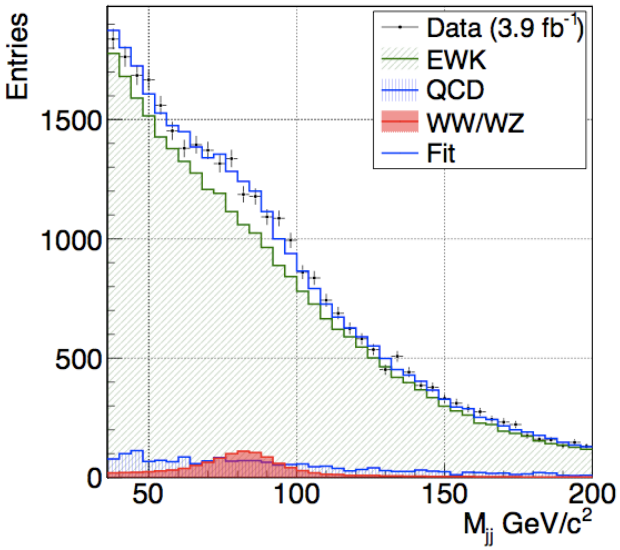




Observation of WW+WZ→$l\nu$+jj Production

- Two analyses
  - Matrix Element (ME) method
    - 2.7 fb^{-1} of data
    - Fit event probability discriminant
      - Based on ME calculation
    - 17.7 ± 3.1(stat) ± 2.4 (syst) pb
      - 5.4σ signal significance
  - M_{jj} fit method
    - 3.9 fb^{-1} of data
    - 14.4 ± 3.1(stat) ± 2.2(syst) pb
      - 4.6σ signal significance
- Combined result
  - CDF: 16.0 ± 3.3 (stat+syst) pb
  - NLO theory: 16.1 ± 0.9 pb



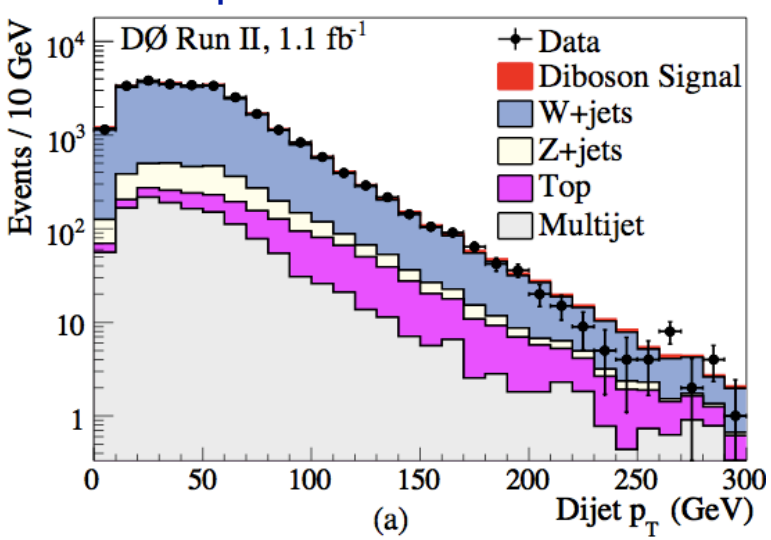


Combined Limits on Anomalous ZWW & γWW TGC

- Four channels combined
  - WW+WZ→*l*ν+jj
  - WW→lν+lν
  - WZ→lν+ll
  - Wγ→lν+γ
  - PRD 80, 053012

	$SU(2)_L \otimes U(1)_Y$		ZWW =γWW	
	minimum	95% CL	minimum	95% CL
Δk_γ	0.07	-0.29, 0.38	0.03	-0.11, 0.18
Δg_1^Z	0.05	-0.07, 0.16	N/A	N/A
λ	0.0	-0.08, 0.08	0.0	-0.08, 0.08
μW	2.02	1.86, 2.16	2.02	1.88, 2.15
qW	-1.0	-1.09, -0.91	-1.02	-1.16, -0.87

Example of distribution sensitive to aTGC



- D0 results with 0.7-1.1 fb^{-1}
  - Most stringent Tevatron result
    - Compatible with individual LEP2 experiments
  - Most stringent result on W magnetic dipole (μW) & electric quadrupole (qW) moments

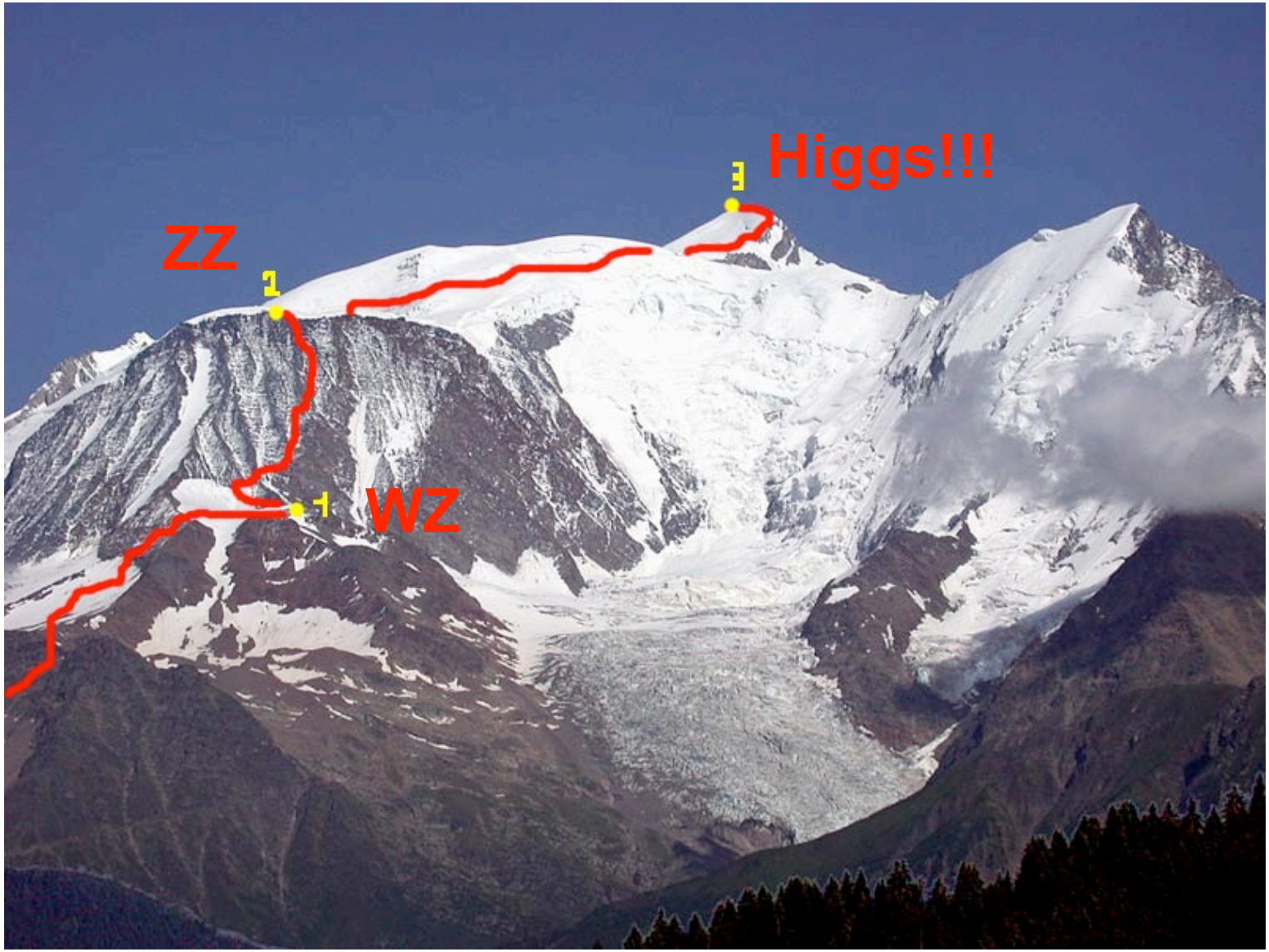
Summary

- CDF & D0 observed and studied all diboson final states
  - All cross sections agree with SM predictions
  - First study of radiation-amplitude zero
  - All TGC agree SM predictions
    - Stringent limits on anomalous TGC
  - No resonant diboson production observed

- First observation of diboson production in hadronic final state
  - Milestone for low mass Higgs searches at Tevatron
  - Both CDF & D0 continue refining techniques for Higgs searches and push the limits

- Most interesting results are yet to come!!

We are almost at the summit of SM!!!



Jets are in the base camp.
LHC will arrive here soon

Backup Slides

$W\gamma$ Production

- Selection
  - Lepton $E_T(P_T)$, MET>20 GeV, $E_T(\gamma)$>9 GeV
  - FSR veto: M_{T3}>120 GeV/c^2
- Acceptance × Efficiency
  - $e\nu+\gamma$: 6.3% ± 0.3%
  - $\mu\nu+\gamma$: 4.5% ± 0.3%
- Dominant Backgrounds
  - $e\nu+\gamma$: W+jet (30%±4%), leX (14%±2.5%)
  - $\mu\nu+\gamma$: W+jet (23%±4.5%), $Z\gamma$ (5%±1%), leX (3.5%±1.7%)
- Leading Systematics
  - Acceptance × Efficiency (5-7%)
  - W+jet background (4-6%)
  - Lumi: 6%

$Z\gamma$ Production

$Z\gamma$ type	FSR+ISR
Photon type	Central Photon
Lepton Channel	$ee\gamma + \mu\mu\gamma$
$\int \mathcal{L}dt(pb^{-1})$	1074 (e) + 2007 (μ)
K-Factor	1.4
$\sigma_{LO}(pb)$	3.4
$\sigma_{NLO}(pb)$	4.5 $\pm$ 0.4
σ^{obs}(pb)	4.6 $\pm$ 0.2(stat.) $\pm$ 0.3(syst.) $\pm$ 0.3(lum)
$N^{bkg}_{\gamma+Jet}$	13.9 $\pm$ 7.1
N^{bkg}_{Z+Jet}	93.9 $\pm$ 25.8
N^{exp}_{SM}	663.2 $\pm$ 30.8
$N^{exp}_{SM} + N^{bkg}_{QCD}$	771.0 $\pm$ 40.8
N^{obs}	778 (390 $ee\gamma$ + 388 $\mu\mu\gamma$)

$Z\gamma$ type	ISR
Photon type	Central Photon
Lepton Channel	$ee\gamma + \mu\mu\gamma$
$\int \mathcal{L}dt(pb^{-1})$	1074 (e) + 2007 (μ)
K-Factor	1.33
$\sigma_{LO}(pb)$	0.91
$\sigma_{NLO}(pb)$	1.21 $\pm$ 0.10
σ^{obs}(pb)	1.20 $\pm$ 0.10(stat.) $\pm$ 0.17(syst.) $\pm$ 0.07(lum)
$N^{bkg}_{\gamma+Jet}$	11.5 $\pm$ 5.6
N^{bkg}_{Z+Jet}	69.5 $\pm$ 19.9
N^{exp}_{SM}	193.5 $\pm$ 9.0
$N^{exp}_{SM} + N^{bkg}_{QCD}$	274.6 $\pm$ 22.6
N^{obs}	273 (154 $ee\gamma$ + 119 $\mu\mu\gamma$)

$Z\gamma$ type	FSR
Photon type	Central Photon
Lepton Channel	$ee\gamma + \mu\mu\gamma$
$\int \mathcal{L}dt(pb^{-1})$	1074 (e) + 2007 (μ)
K-Factor	1.4
$\sigma_{LO}(pb)$	2.4
$\sigma_{NLO}(pb)$	3.3 $\pm$ 0.3
σ^{obs}(pb)	3.4 $\pm$ 0.2(stat.) $\pm$ 0.2(syst.) $\pm$ 0.2(lum)
$N^{bkg}_{\gamma+Jet}$	2.4 $\pm$ 1.6
N^{bkg}_{Z+Jet}	24.3 $\pm$ 5.9
N^{exp}_{SM}	469.7 $\pm$ 21.8
$N^{exp}_{SM} + N^{bkg}_{QCD}$	496.4 $\pm$ 22.6
N^{obs}	505 (236 $ee\gamma$ + 269 $\mu\mu\gamma$)

WW Production

- D0 analysis
  - Selection
    - Leading lepton $E_T(P_T)>25$ GeV
    - Sub-leading lepton $E_T(P_T)>15$ GeV
    - $\Delta R>0.8$ (ee), 0.5 (eμ, μμ)
    - ee, eμ, μμ-events: MET>45, 20, 35 GeV
    - eμ-events: MET>40 GeV if $\Delta\varphi(e\mu)>2.8$
    - $\Delta\varphi(\mu\mu)<2.45$
    - ee, eμ, μμ-events: $Q_T<20$, 25, 16 GeV/c^2
  - Acceptance*Efficiency
    - ee, eμ, μμ-events: 7.18%, 13.43%, 5.34%
  - Dominant Backgrounds
    - W+jets & W+γ (ee, eμ events), ttbar, WW & ZW
  - Leading Systematics
    - Estimation of W+jets & W+γ backgrounds

WW Production

- Selection
  - Leading lepton $E_T(P_T)$>20 GeV
  - Sub-leading lepton $E_T(P_T)$>10 GeV
  - ee, μμ,(eμ)-events: MET>25 (15) if Δφ(l-MET)>π/2
  - ee, μμ,(eμ)-events: MET*Δφ>25 (15) if Δφ(l-MET)<π/2
  - M_{ll}>16 GeV/c^2
  - 3rd lepton veto

CDF Run II Preliminary	$\int \mathcal{L} = 3.6$ fb^{-1}
Process	Events
Z/γ^*	79.8 ± 18.4
WZ	13.8 ± 1.9
$W\gamma$	91.7 ± 24.8
W+jets	112.7 ± 31.2
ZZ	20.7 ± 2.8
$t\bar{t}$	1.3 ± 0.2
Total Background	320.1 ± 46.8
WW	317.6 ± 54.1
Signal+Background	637.6 ± 79.6
Data	**654**

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet
Cross Section		6.0%	6.0%	10.0%	5.0%	10.0%	
Acceptance							
PDF Model	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%	
Higher-order Diagrams	5.0%	10.0%	10.0%	10.0%		10.0%	
Jet Modeling	2.0%				21.0%	4.0%	
Conversion Modeling						20.0%	
Jet Fake Rates							27.7%
MC Run Dependence	3.8%			1.0%		5.0%	
Lepton ID Efficiencies	2.0%	1.7%	2.0%	2.0%	1.9%	1.4%	
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%	7.0%	
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%	5.9%	

WZ Production

Source	Expected ± Stat ± Syst ± Lumi
Z+jets	2.45 ± 0.48 ± 0.48 ± 0.00
ZZ	1.53 ± 0.01 ± 0.16 ± 0.09
$Z\gamma$	1.03 ± 0.06 ± 0.35 ± 0.06
$t\bar{t}$	0.17 ± 0.01 ± 0.03 ± 0.01
WZ	16.45 ± 0.03 ± 1.74 ± 0.99
Total	21.63 ± 0.48 ± 2.25 ± 1.15
Observed	**25**

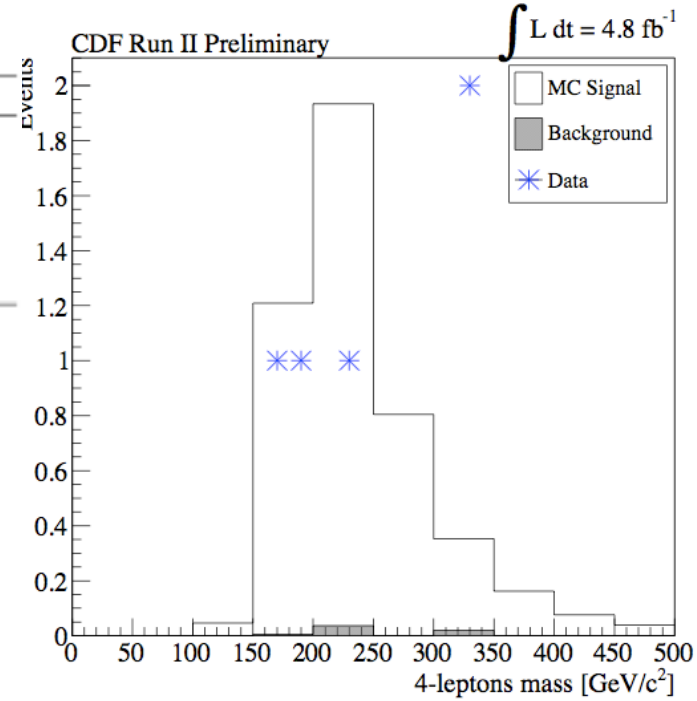
- Selection
  - Leading lepton $E_T(P_T)$>20 GeV
  - Sub-leading lepton $E_T(P_T)$>10 GeV
  - MET>25 GeV
  - 76 GeV/c^2<M(l^+l^-)<106 GeV/c^2

	Fractional Uncertainties (%)					
Source	WZ	ZZ	$Z\gamma$	$t\bar{t}$	Z+jets	$\sigma(WZ)$
Cross-section	-	10.0	22.0	15.0	-	2.0
Energy Scale	1.0	1.0	1.0	-	-	1.1
$\not{E}_T$ Modeling	1.0	1.0	25.0	1.0	-	2.4
PDF Uncertainty	2.0	2.0	2.0	2.0	-	2.3
LepId $\pm 1\sigma$	1.9	2.0	1.9	1.8	-	2.2
Trigger Eff	1.5	1.9	5.7	2.4	-	2.0
Jet→Lepton Mis-Id	-	-	-	-	19.4	2.4
Total	3.5	10.7	33.9	15.5	19.4	5.6
Luminosity	6.0	6.0	6.0	6.0	-	6.8

ZZ Production

Candidate	leptons	M_{ll-1}	M_{ll-2}	4 lepton invariant mass
1	$trk\mu/\mu\mu$	90.5 GeV/c^2	88.5 GeV/c^2	324.8 GeV/c^2
2	$trk\mu/\mu\mu$	91.6 GeV/c^2	94.2 GeV/c^2	169.4 GeV/c^2
3	$ee/\mu\mu$	93.0 GeV/c^2	86.4 GeV/c^2	191.9 GeV/c^2
4	$ee/\mu\mu$	93.3 GeV/c^2	79.7 GeV/c^2	229.2 GeV/c^2
5	$\mu\mu/\mu\mu$	91.7 GeV/c^2	55.1 GeV/c^2	325.0 GeV/c^2

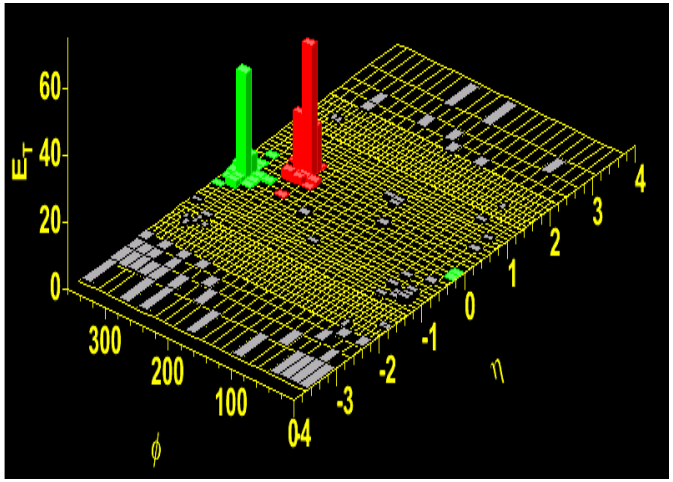
Fractional Uncertainty (%)	
NLO Acceptance	10.0 %
Cross - section	10.0 %
PDF uncertainty	2.7 %
Luminosity	6.0 %
LeptonID $\pm 1\ \sigma$	3.6 %
Trigger Efficiency	2.1 %
Background Modeling	67 %



- Acceptance ~7%

First Observation of VV→MET+jj

- 44,910 candidates in 3.5 fb^{-1} of data

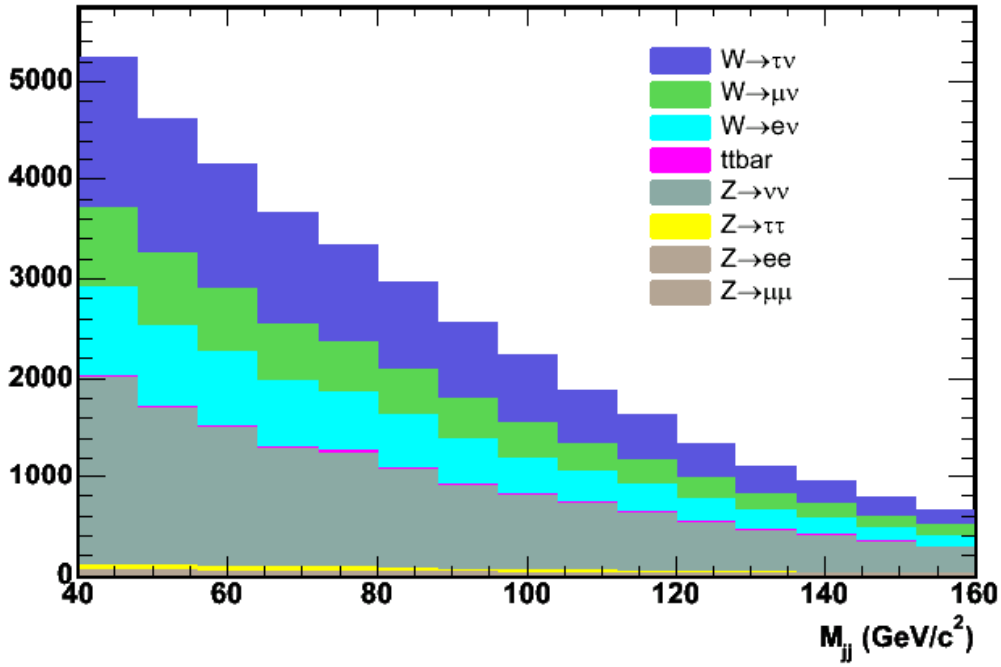


QCD multijet rejection

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

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

VV→MET+jj: EWK Background



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**

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

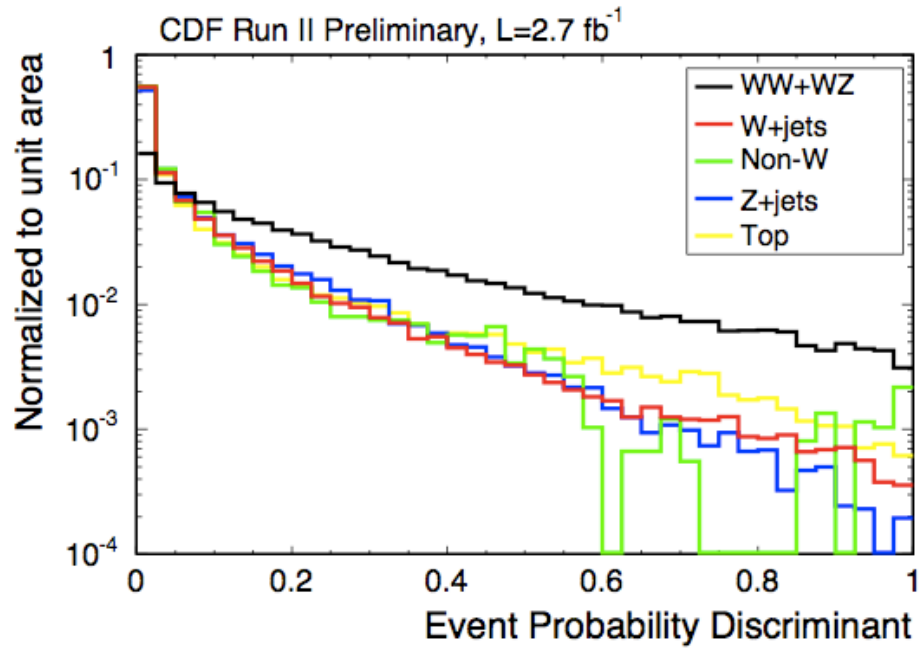
VV→MET+jj: Systematics

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
  - Jet energy resolution

Matrix Element Method

- Define probability of an event originating from a specific process by evaluating differential cross sections
  - Integrate over detector response functions, parton distribution functions, and z-component of MET
- Evaluate probabilities of signal and background processes and define Event Probability Discriminant (EPD)



$$EPD = \frac{P_S}{P_S + P_B} = \frac{P_{WW} + P_{WZ}}{P_{WW} + P_{WZ} + \boxed{P_{s-chan} + P_{t-chan}} + \boxed{P_{Wgj} + P_{Wcc} + P_{Wbb} + P_{Wcj}}}$$

Single top

W+jets

WW+WZ→$l\nu$+jj: Backgrounds & Event Selection

- Lepton requirements
  - Exactly one central (|η|<1) electron or muon with P_T>20 GeV
  - Strict ID requirements
    - Significantly reduced signal acceptance
- Jet requirements
  - Exactly two jets with E_T>25 GeV & |η|<2
  - No additional jets with E_T>12 GeV
  - 2nd jet not aligned with MET
- W-boson selection
  - MET>40 (20) GeV for electron (muon) events
  - M_T(W)>70 (10) GeV for electron (muon) events
- Signal & Background simulation
  - Pythia: signal, single top, top pair
  - Alpgen+Pythia: Z+jets & W+jets

Process	Expected # of Events
WW signal	**446 ± 29**
WZ signal	**79 ± 6**
W+jets	**10175 ± 305**
Z+jets	584 ± 88
QCD multijet	283 ± 113
Top pair	131 ± 18
Single top	110 ± 11
Total predicted	**11808 ± 340**
Observed	**11812**