Electroweak Physics at the Tevatron

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On behalf of the CDF and D0 Collaborations

La Thuile
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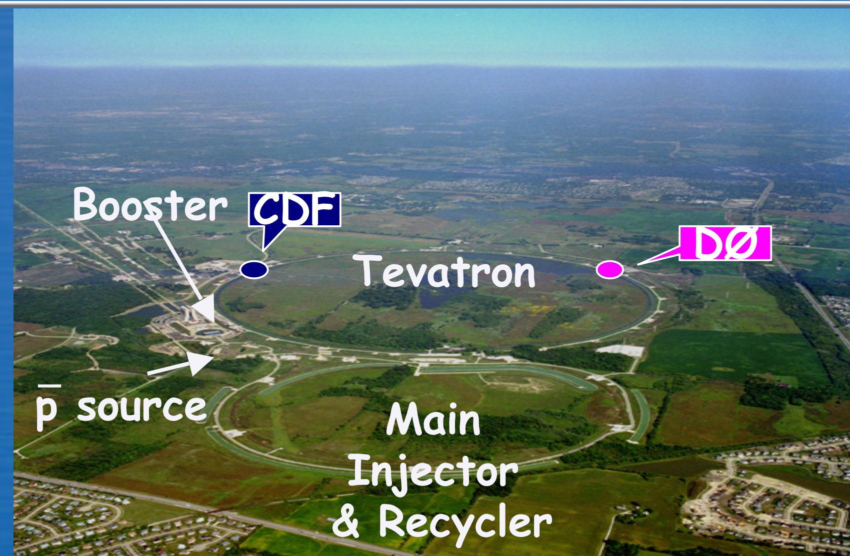
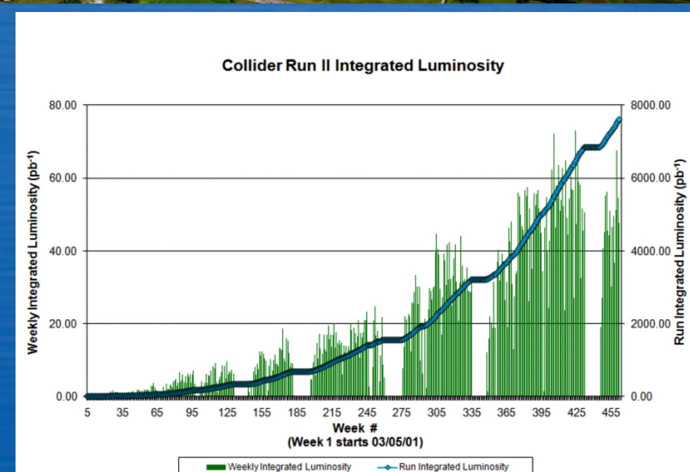
Tevatron at Fermilab

- p $\bar{p}$ collisions at 1.96 TeV
- More than 7 fb^{-1} data on tape per experiment
- Running in 2011: 10 -12 fb^{-1} per experiment

Process	Events in 1 fb^{-1}
WW→lvlv	523
ZW→ll+lv	111
ZZ→ll+ll	~7
WW→jjlv	5,100
WZ→jjlv+jjvv	1,300
ZZ→vvjj	420
H_{160}→WW→lvlv ??	22
WH_{120}→lv+bb ??	22
ZH_{120}→vv+bb ??	13

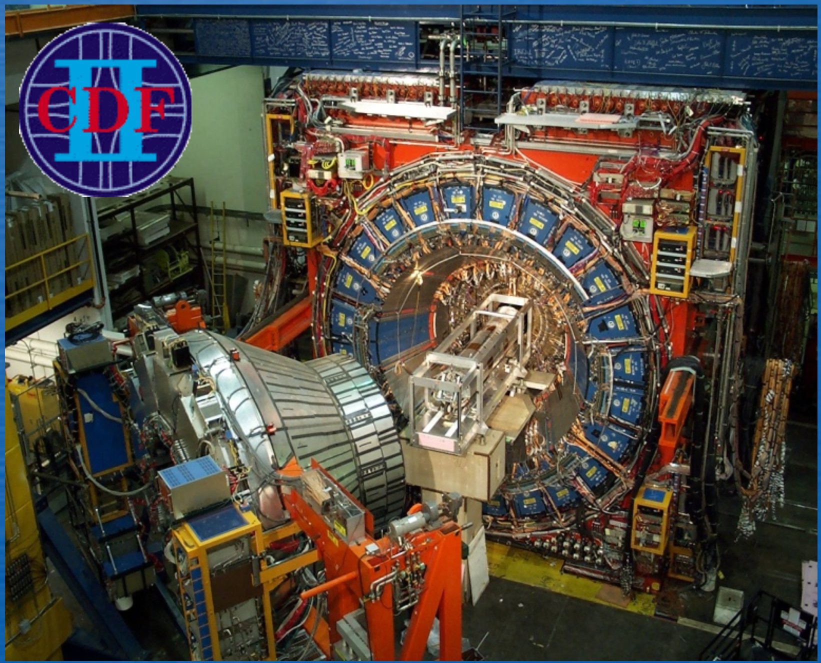


Show analyses up to 5.1 fb^{-1} of data



CDF II and D0 Detectors

- Multipurpose Detectors
    - Silicon tracking, central tracker , calorimeter, muon chamber
- Solid operations with high efficiency: 80 - 90%
- Broad Physics Program: B-Physics, QCD, Top, Higgs and new Physics searches, of course EWK



Outline

We will focus on Diboson Physics

- $Z\gamma$
- WW and ZZ with leptons
- Dibosons with jets

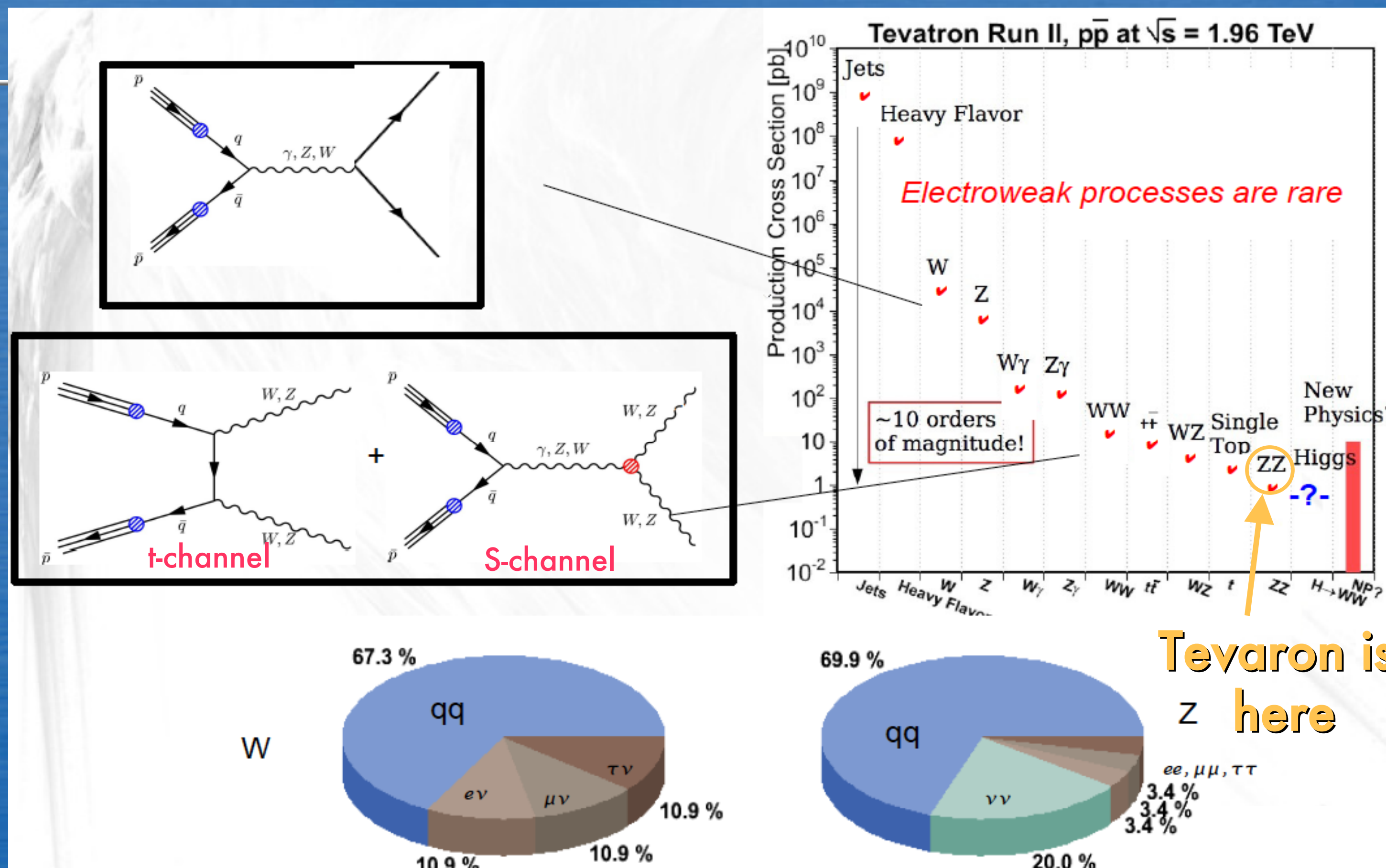
TGC
(Also $WW+WZ \rightarrow l\nu + jj$)

W mass covered in next talk by Alexander Melnitchouk

5

Diboson Production

S-channel probes triple gauge coupligns (TGC)

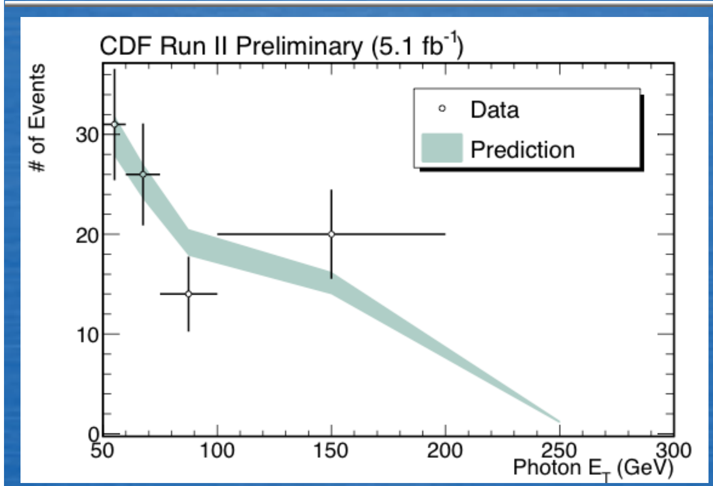


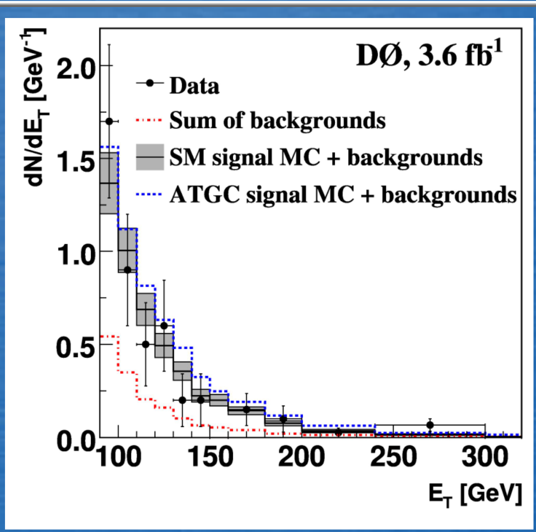
Tevatron is in the Diboson era: now with Jets

Zγ Production

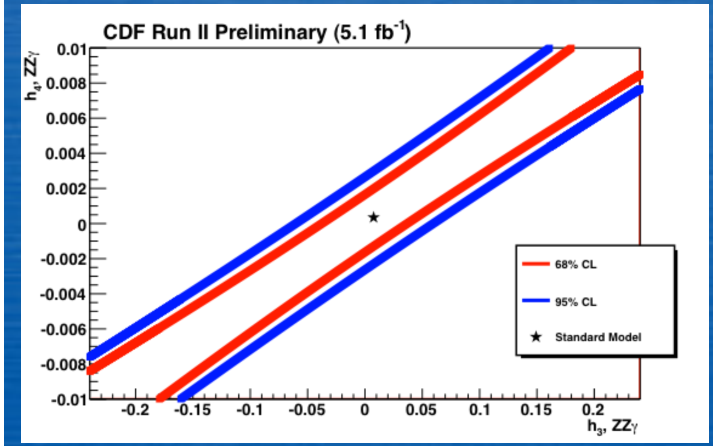
D0: Z(νν) + γ in 3.6 fb^{-1}

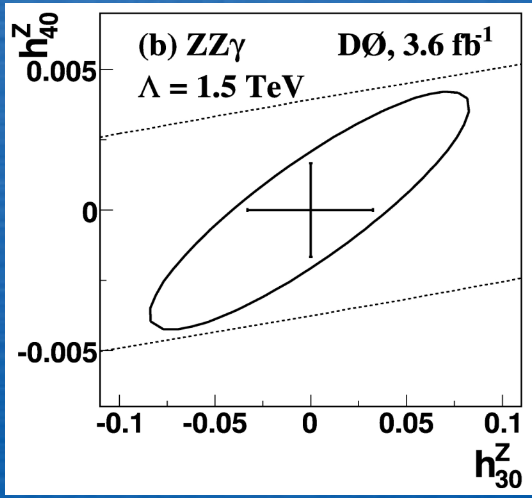
PRL 102, 201802 (2009)





CDF: Z(ll) + γ in 5.1 fb^{-1}





WW→lν + lν

- Dominant background for H→WW (same analysis techniques)
- Test SM prediction: xsec can be enhanced by NP or Higgs
- Look for anomalous TGC

Results:

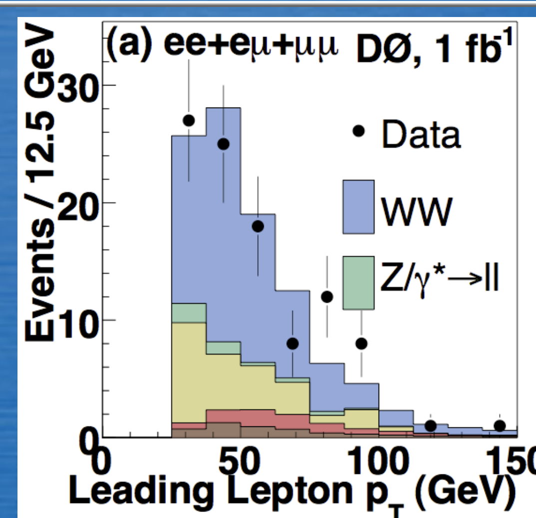
- **CDF: $12.1 \pm 0.9^{+1.6}_{-1.4}$(syst) pb**

  arXiv:0912.450

- **D0: 11.5±2.1(stat+syst)±0.7(lumi) pb**

  PRL 103, 191801 (2009)

NLO theory 11.66 ± 0.70 pb



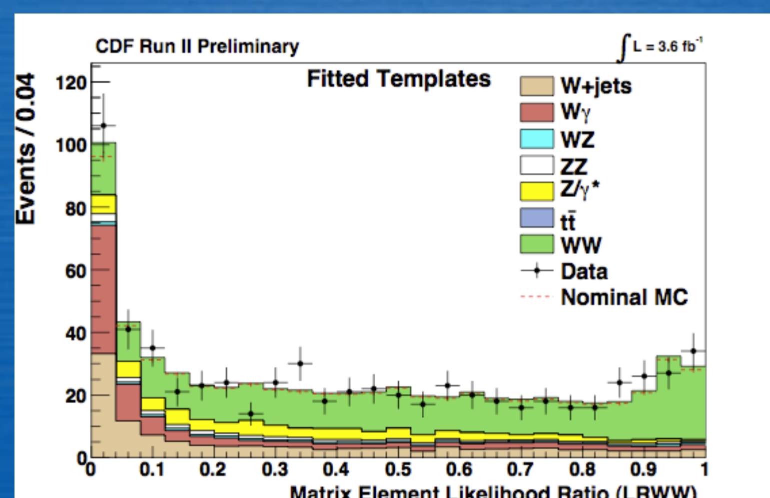
TGC

CDF Preliminary Results at $3.6\mathrm{fb}^{-1}$

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



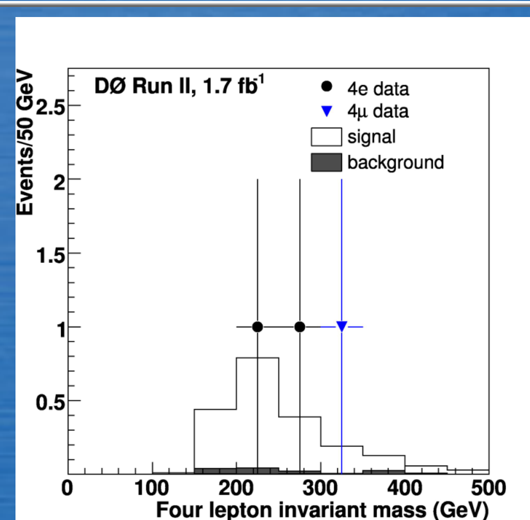
ZZ → ll+ νν & ll+ll

Smallest Diboson SM production x-section

- D0 observed ZZ → ll+ll in 1.7 fb^{-1}
  - Three events with statistical significance of 5.3 σ
- Significance rises to 5.7 σ if combined to ZZ → ll+ νν

$$\sigma(ZZ) = 1.75^{+1.27}_{-0.86}\ (\mathrm{stat.}) \pm 0.13\ (\mathrm{syst.})\ \mathrm{pb}$$

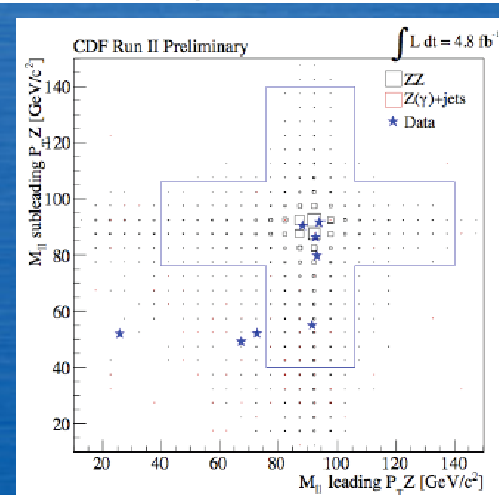
PRL 101, 171803 (2008)



- CDF observed ZZ → ll+ll in 4.8 fb^{-1}
  - Five events with statistical significance of 5.7 σ

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

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



http://www-cdf.fnal.gov/physics/ewk/2009/ZZllll/ZZWeb/cdf9910_ZZ_4leptons_public.pdf

Combined limits on Anomalous ZWW & γWW TGC

Combination of four channels:

PRD 80, 053012

- WW + WZ→ lν + jj
- WW → lν + lν
- WZ → lν + ll
- Wγ → lν + γ

Results with 0.7 - 1.1 fb^{-1}

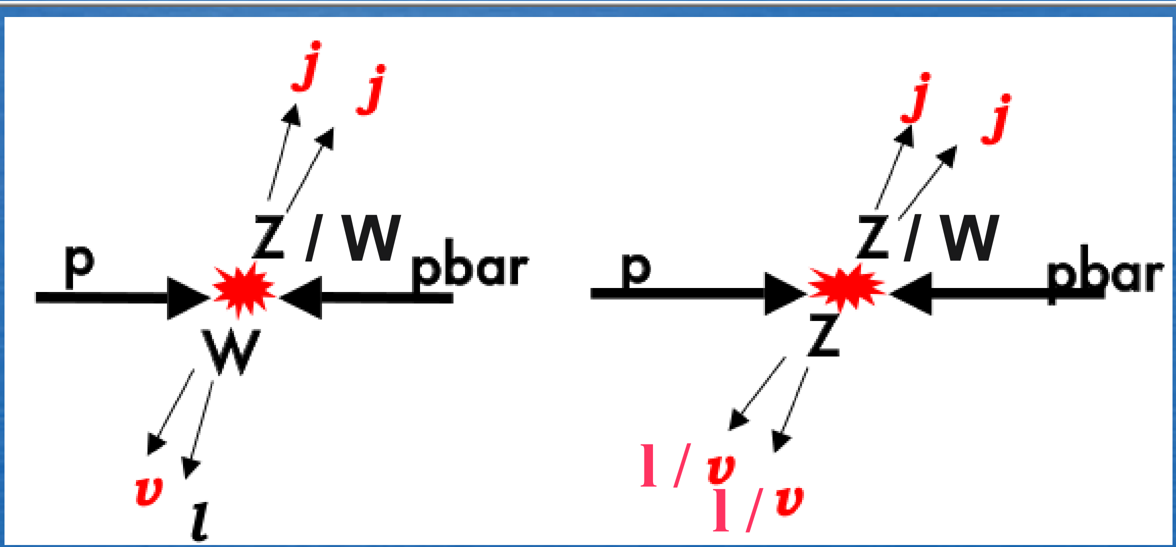
- Most stringent Tevatron result

- Compatible with individual LEPII experiments

Results respecting $SU(2)_L \otimes U(1)_Y$ symmetry			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa_\gamma$	0.07	$[-0.13, 0.23]$	$[-0.29, 0.38]$
Δg_1^Z	0.05	$[-0.01, 0.11]$	$[-0.07, 0.16]$
λ	0.00	$[-0.04, 0.05]$	$[-0.08, 0.08]$
μ_W	2.02	$[1.93, 2.10]$	$[1.86, 2.16]$
q_W	-1.00	$[-1.09, -0.91]$	$[-1.16, -0.84]$
Results for equal-couplings			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa$	0.03	$[-0.04, 0.11]$	$[-0.11, 0.18]$
λ	0.00	$[-0.05, 0.05]$	$[-0.08, 0.08]$
μ_W	2.02	$[1.94, 2.09]$	$[1.88, 2.15]$
q_W	-1.02	$[-1.09, -0.94]$	$[-1.16, -0.87]$

- Most stringent result on W magnetic dipole (μW) and electric quadrupole (qW) moments.

WW - WZ - ZZ with jets



Similar to low mass Higgs processes:

- WH
- ZH

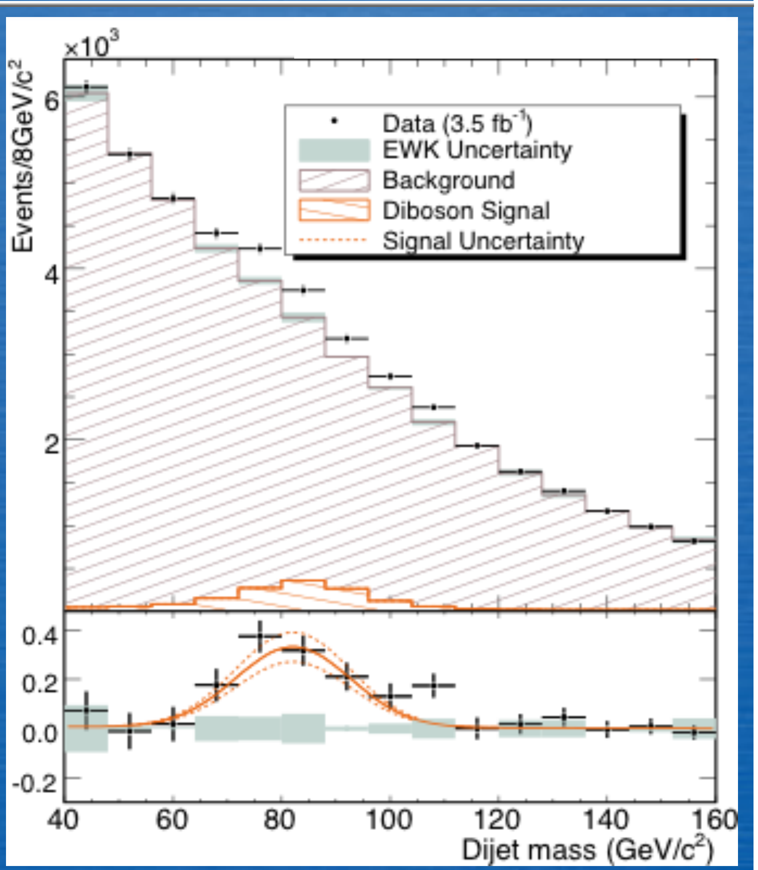
- Dibosons with hadronic final state to test SM TRUE
- Used in TGC limits TRUE
- But... :
  - How can we talk about low mass Higgs if we are not able to make a great job with Dibosons into jets ?

Observation of VV → MET + jj

- Search for νν and lν final states.
- Acceptance for WW, WZ and ZZ events.
- Event selection:
  - Missing E_T > 60 GeV;
  - 2 jets E_T > 25 GeV, |h| < 2.0;
  - Missing E_T significance > 4;
  - Missing E_T-jet $\Delta\phi$ > 0.4.
- Missing E_T model to enanche QCD rejection.
- Sysytematic uncertaintiy on V+jj background shape checked with γ+jj events.

In 3.5 fb^{-1}

1516 ± 239(stat) ± 144(syst) events
5.3 σ Significance



σ(pp→VV) , V=W,Z
18.0 ± 2.8(stat) ± 2.4(syst) ± 1.1(lum) pb

NLO Theory = 16.8 ± 0.5 pb

PRL 103, 091803 (2009)

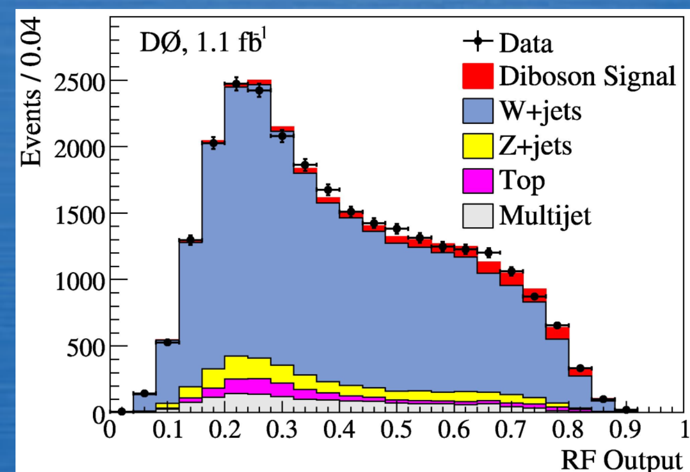
WW + WZ → lν + jj

- Similar to WH → lν + jj
- Same Analysis Technique
    - Validate multivariate technique to extract small signal in large background

In 1.1 fb-1:

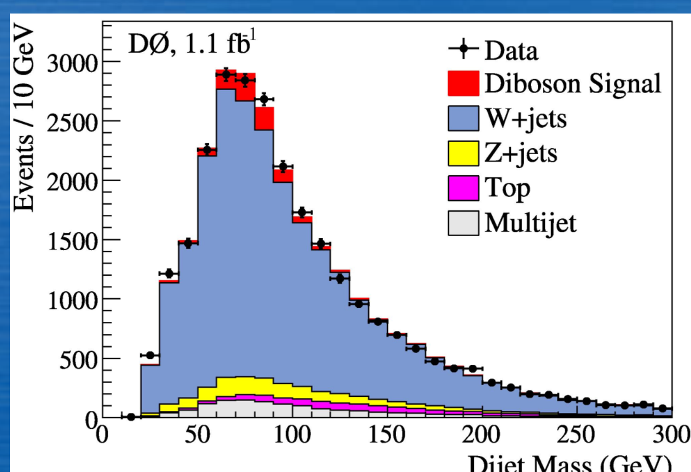
σ(pp→WW + WZ) =
20.2 ± 2.5(stat) ± 3.6(syst) ± 1.2(lum) pb

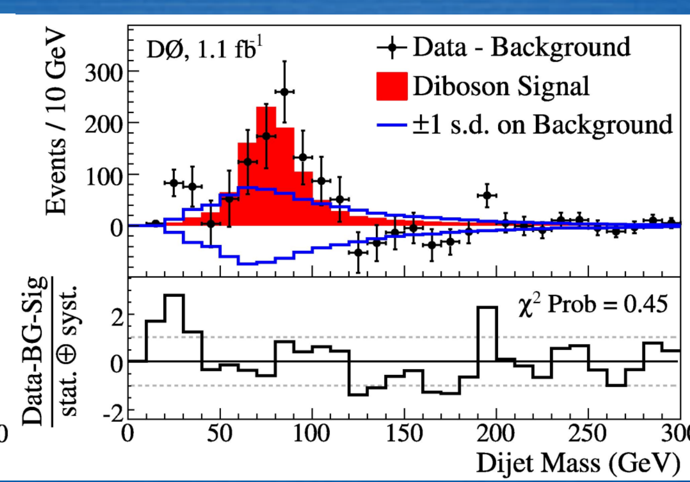
NLO Theory = 16.1 ± 0.9 pb



Signal Significance 4.4 σ
First Evidence

PRL 102, 161801 (2009)





WW + WZ → $l\nu$ + jj

- Two analyses:
  - Matrix Element Method: First observation in 2.7 fb^{-1}

$\sigma(pp \rightarrow WW + WZ) = 17.7 \pm 3.1(stat) \pm 2.4(syst)$ pb

  - Mjj Fit : 4.6 σ significance in 3.9 fb^{-1}

$\sigma(pp \rightarrow WW + WZ) = 14.4 \pm 3.1(stat) \pm 2.2(syst)$ pb

  - Combined Result

$\sigma(pp \rightarrow WW + WZ) = 16.0 \pm 3.3(stat + syst)$ pb

Now Updated

arXiv:0911.444

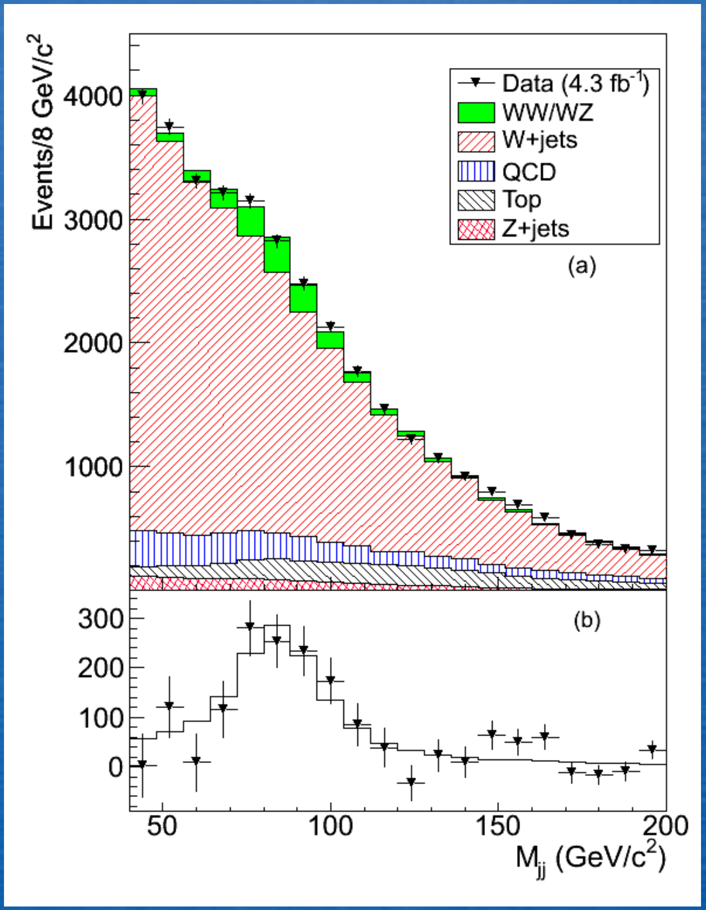
WW + WZ → lν + jj (Mjj)

- Look for a lepton and MET → W
- Look for at least two jets with E_T>20 GeV
- Compute Mjj of the two leading jets → W/Z
- Require Pt(jj) > 40 GeV/c to have smooth background
- Fit Mjj distribution

In 4.3 fb^{-1}

1582 ± 275(stat) ± 107(syst) events
5.2 σ Significance

σ(pp→WW + WZ) =
18.2 ± 3.3(stat) ± 2.5(syst) pb

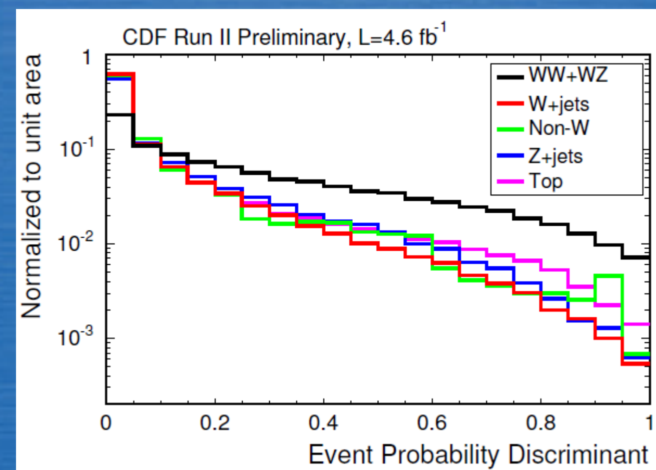


Mjj peak observed

$WW + WZ \rightarrow l\nu + jj$ (ME)

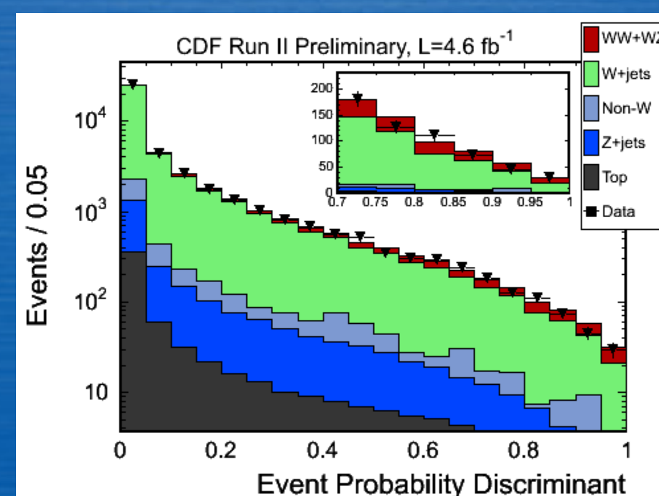
- Same technique of $WH \rightarrow l\nu + bb$
- Evaluate Matrix element of sample components
- Combine into EPD

- $EPD = P_{sig} / (P_{BG} + P_{sig})$
  - $P_{sig} = P_{WW} + P_{WZ}$
  - P_{BG} = sum of probabilities of BG processes



In 4.6 fb^{-1}

5.4 σ Significance

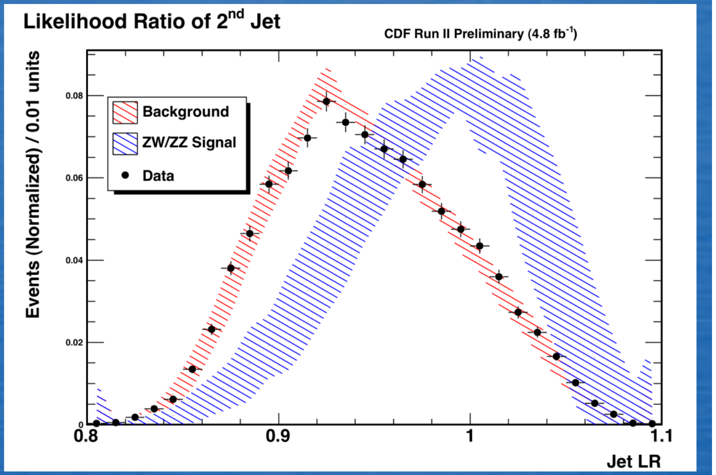


$\sigma(pp \rightarrow WW + WZ)$ =
16.6 + 3.5 - 3.0 (stat+ syst) pb

ZW + ZZ → ll + jj

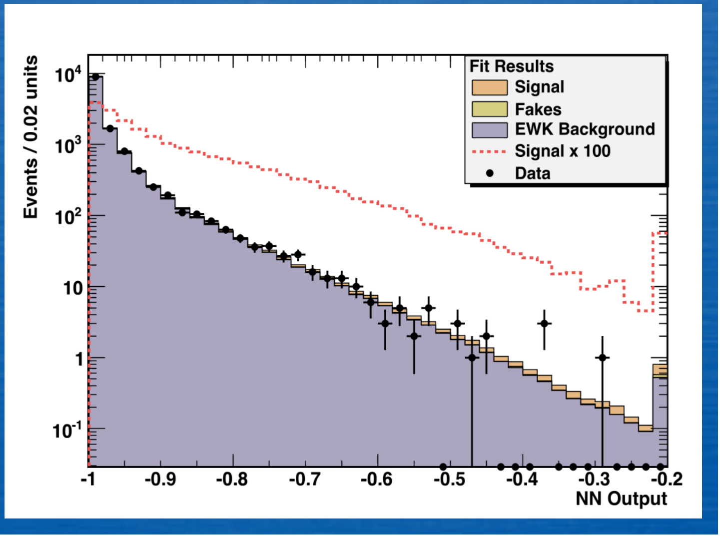
- Combination of WZ and ZZ still unobserved
    - Branching ratio of Z → leptons small
    - Z+ jets background is very large
    - Motivates new quark-gluon discriminant

Jet Likelihood Ratio:
Quark/Gluon Discriminant



- Energy in *q* jets less spatially spread than in *g* jets
- Compare ΔR distribution of calorimeter tower pairs within jet to typical quark or gluon (from Alpgen Monte Carlo)
    - Quantized as Jet LR: larger = more quark-like

- Build NN discriminant
- Fit of 4.8 fb^{-1} data to S+B template yields:
    - 86.4 ± 107.7 signal events
    - 13603 ± 840 bkg events
- p-value obs/exp: 0.167/0.097



•Set a limit on σ_{ZW+ZZ} of
$\sigma_{obs}/\sigma_{exp}$ < 2.46 at 95% CL

Summary

- Electroweak Physics very active at the Tevatron
- Tevatron is setting stringent limits on TGC
- Diboson signals in hadronic final states well established: new standard candle for Physics with jets ?
- WZ → lν + bb and WZ/ZZ → MET + bb next frontier (also Higgs, of course)
- Listen to next talk for another Tevatron EWK hot topic: W mass

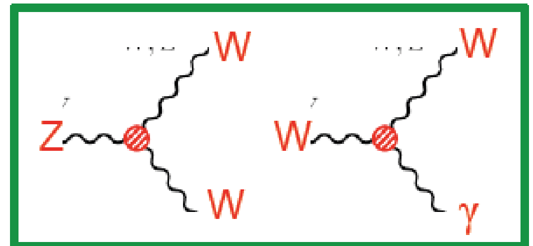
Tevatron is going fast, very fast.

Btw. This guy
(Simone Origone) is Italian.
Of course…

Backup

Triple Gauge Couplings

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



$$
\begin{aligned}
\frac{\mathcal{L}_{\text{eff}}^{VWW}}{g_{VWW}} = & \; i g_1^V \left(W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu} \right) \\
& + i \kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda} \\
& - g_4^V W_\mu^\dagger W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right) \\
& + g_5^V \epsilon^{\mu\nu\lambda\rho} \left(W_\mu^* \partial_\lambda W_\nu - \partial_\lambda W_\mu^\dagger W_\nu \right) V_\rho \\
& + i \tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu} + i \frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu \tilde{V}^{\nu\lambda}
\end{aligned}
$$

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→lν + γ production
- **Isolate WW γ coupling**

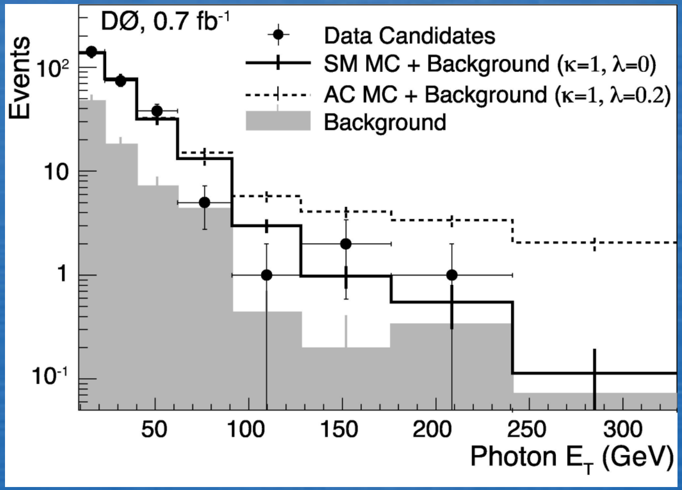
Results
- **95% CL on a TGC:**
  - **$0.49<k_\gamma<1.51$**
  - **$-0.12<\lambda_\gamma<0.13$**

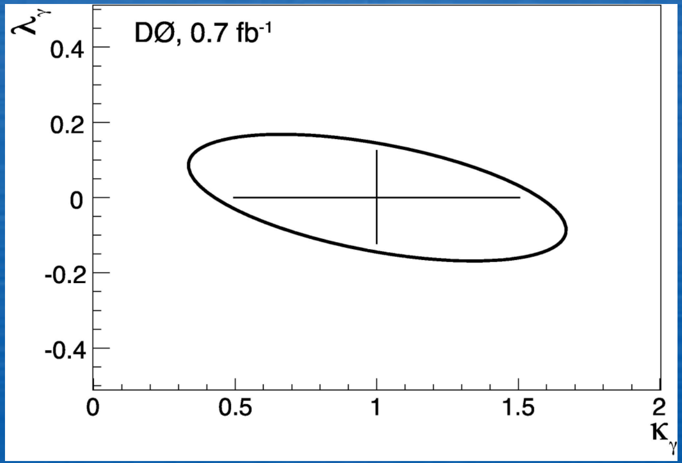
PRL 100, 241805 (2008)

- **σ=14.8±1.5(stat)±1.0(syst)±1.0(lum) pb**

PRD 71, 091108 (2005)

NLO theory: 16 ± 0.4 pb



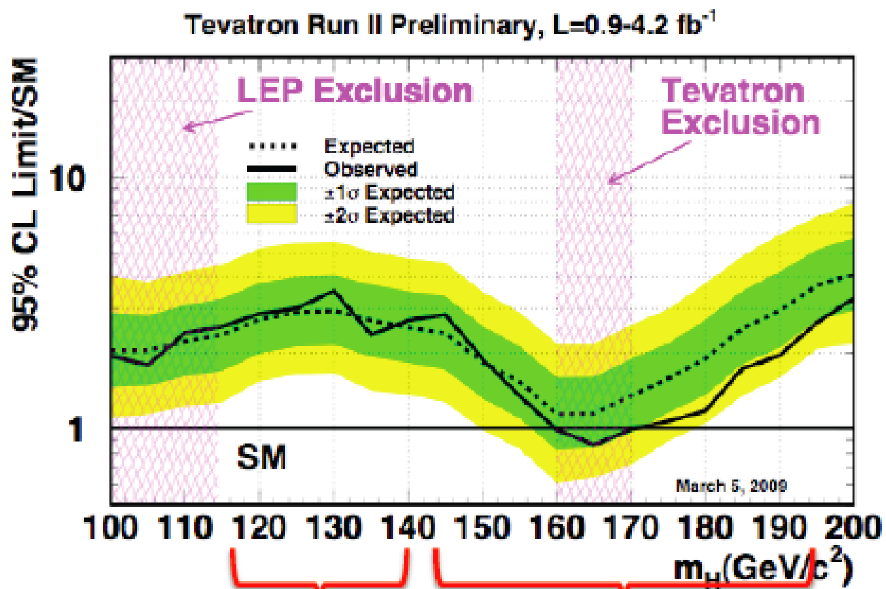


Road to Higgs is Paved with Dibosons

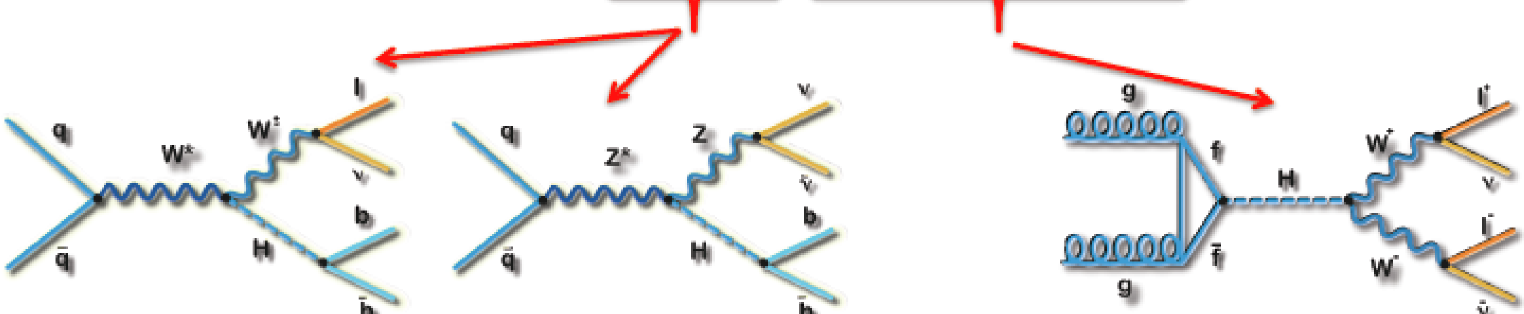
- Dibosons need to be well measured and understood before exclusion or observation of Higgs can be claimed

$WH \to l\nu + bb$ similar to **$WW + WZ \to l\nu + jj$**

$ZH \to \nu\nu + bb$ similar to **$WZ + ZZ \to \nu\nu + jj$**



Direct **$WW \to l\nu + l\nu$** dominant background for **$H \to WW \to l\nu + l\nu$**



WW Production

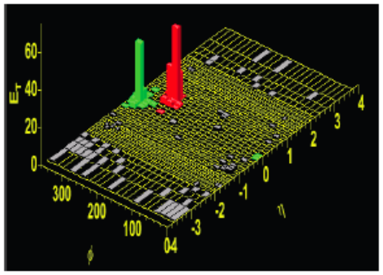
- D0 analysis
  - Selection
    - Leading lepton $E_T(P_T)>25$ GeV
    - Sub-leading lepton $E_T(P_T)>15$ GeV
    - $\Delta R>0.8$ (ee), 0.5 (eμ, μμ)
    - ee, eμ, μμ-events: MET>45, 20, 35 GeV
    - eμ-events: MET>40 GeV if $\Delta\varphi(e\mu)>2.8$
    - $\Delta\varphi(\mu\mu)<2.45$
    - ee, eμ, μμ-events: $Q_T<20, 25, 16$ 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 CDF

- 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

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%*	

$VV \rightarrow MET + jj$



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 $\lvert\eta\rvert$	<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/c² – 160 GeV/c²
Jet timing	<4.5 ns

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**

CDF: WW + WZ → lν + jj

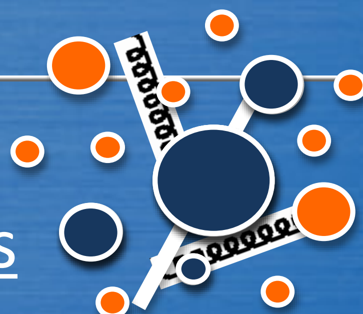
Mjj

Source	e %	μ %
QCD shape	6.4%	4.8 %
EWK shape	9.8%	6.6%
JES	5.8%	5.9%
JER	1.4%	1.1 %
TOTAL (Extraction)	13.1 %	10.1 %
Luminosity	6%	6%
Lepton Acceptance	2%	2%
ISR	2.7%	2.0%
FSR	0.7%	4.2%
PDF	2.0%	2.0 %
TOTAL (Acceptance)	15.0 %	13.0%

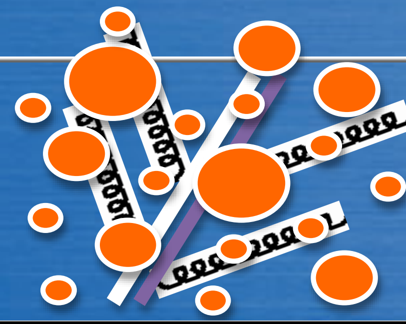
ME

Source	Expected contribution WW+WZ cross section uncertainty
Statistics	14%
JES	8%
Q^2	7%
ISR / FSR	4%
Luminosity	6%
JER	<4%
p_{Tjj} mismodeling	<4%
PDFs	<4%
Efficiency	<4%
Total systematics	16%
Total	21%

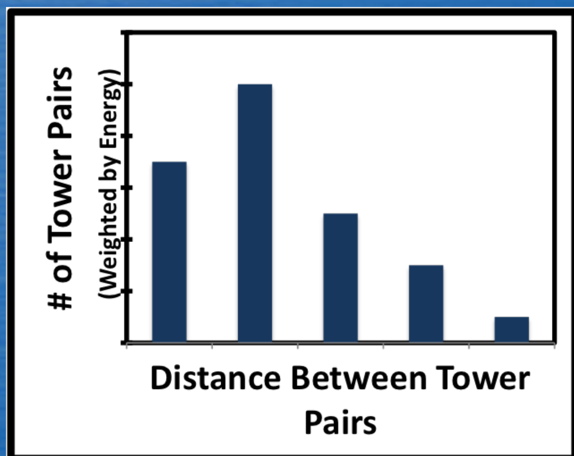
ZW + ZZ → ll + jj

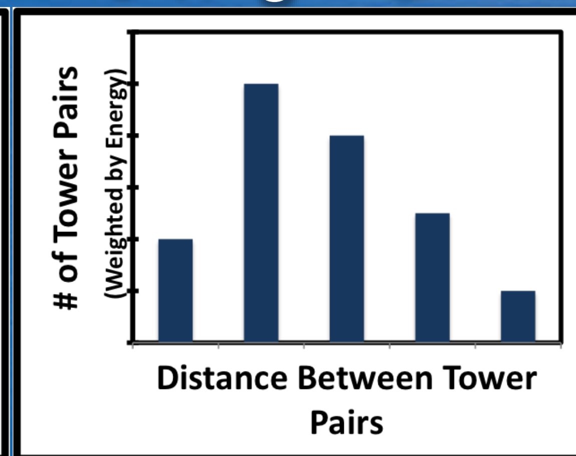


(Light) Quarks



Gluons





$$LR = \prod_{i=0}^{n} \left(\frac{q_i}{g_i}\right)^{j_i},$$

Monte Carlo Systematic	Background Rate Change (%)	Signal Rate Change (%)
Jet Energy Scale ($-1\sigma/+1\sigma$)	-12.6 / $+14.0$	-3.7 / $+3.4$
Jet Energy Resolution	-2.5	-0.67
Lepton Energy Scale ($-1\sigma/+1\sigma$)	-0.65 / $+0.66$	-0.45 / $+0.47$
Lepton Energy Resolution	$+0.14$	$+0.07$
Jet LR	Shape Only	Shape Only
ISR & FSR		$-0.43/+1.2$
Z P_T	Shape Only	Shape Only