Diboson Physics at the Tevatron

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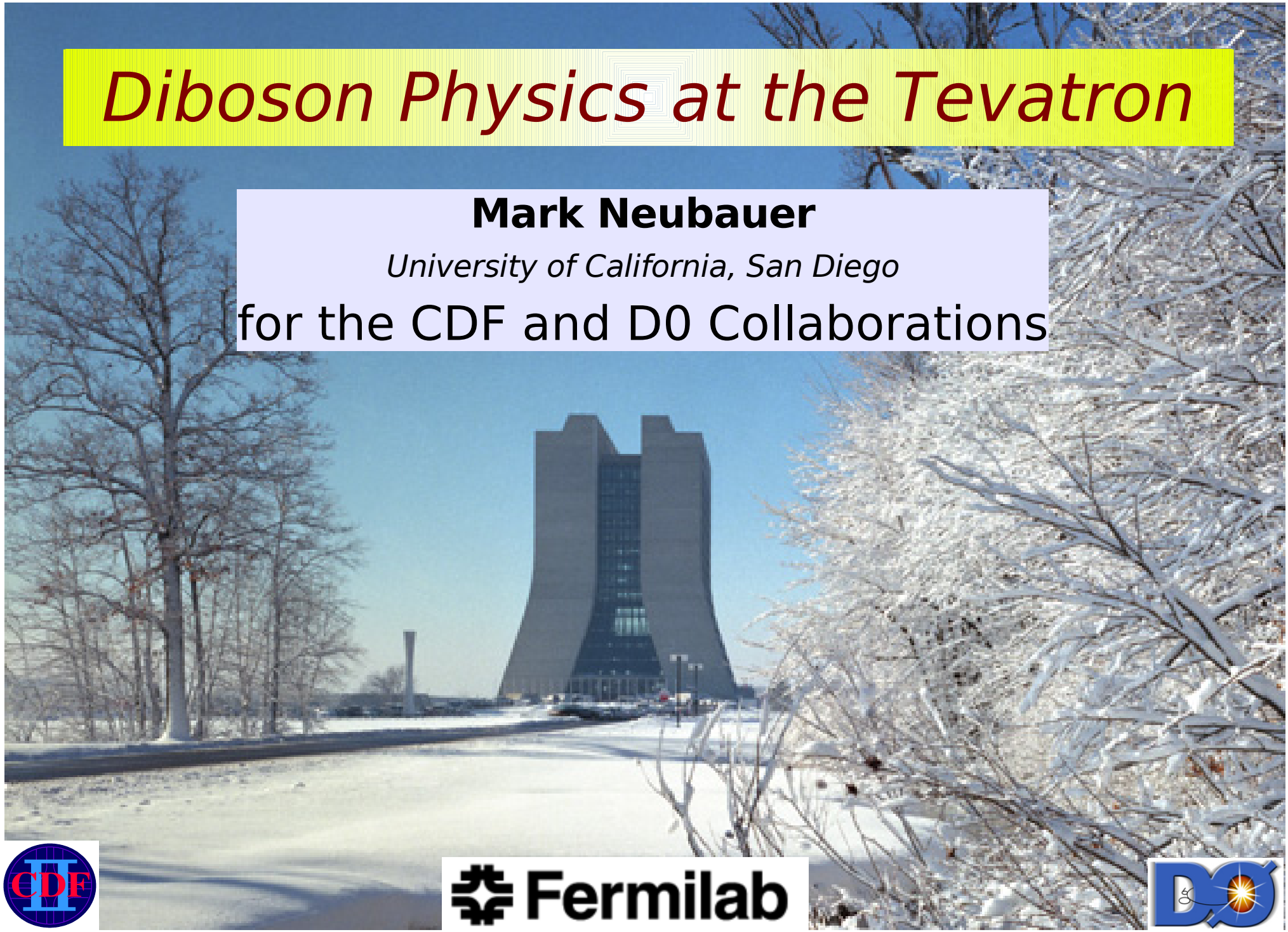
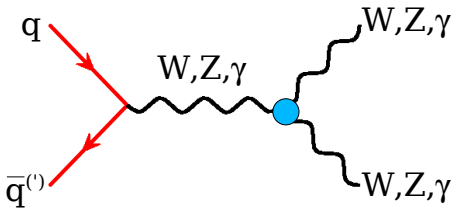
for the CDF and D0 Collaborations



Why Study Dibosons @ Tevatron?

- Probe non-Albelian nature of $SU(2)_L \otimes U(1)_Y$ → gauge boson self-interactions (triple, quartic)

  → Diboson production is sensitive to new physics (NP) in trilinear gauge couplings (TGC) and tests models of EWSB



- Tevatron ($p\bar{p}$) complementary to LEP (e^+e^-)

  → Tevatron sensitive to different combinations of TGC couplings

  → Tevatron explores higher $\hat{s}$ than LEP

$$
\begin{aligned}
q\bar{q}' &\to W^{(*)} \to W\gamma : WW\gamma \text{ only} \\
q\bar{q}' &\to W^{(*)} \to WZ : WWZ \text{ only} \\
q\bar{q} &\to Z/\gamma^{(*)} \to WW : WW\gamma, WWZ \\
q\bar{q} &\to Z/\gamma^{(*)} \to Z\gamma : ZZ\gamma, Z\gamma\gamma \\
q\bar{q} &\to Z/\gamma^{(*)} \to ZZ : ZZ\gamma, ZZZ
\end{aligned}
$$

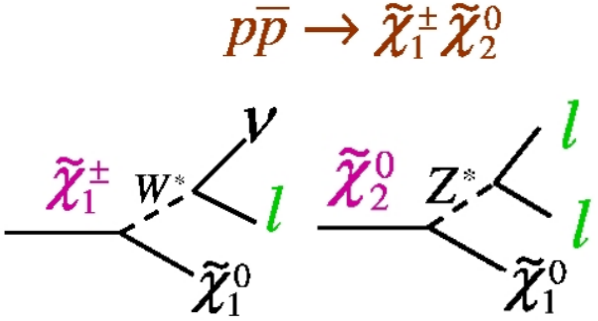
Absent in SM

- SM diboson production important background for many high pt analyses (e.g. H→WW, ZH/WH, SUSY, $t\bar{t}$)

  → Demonstrates experimental sensitivity to multi-lepton final states

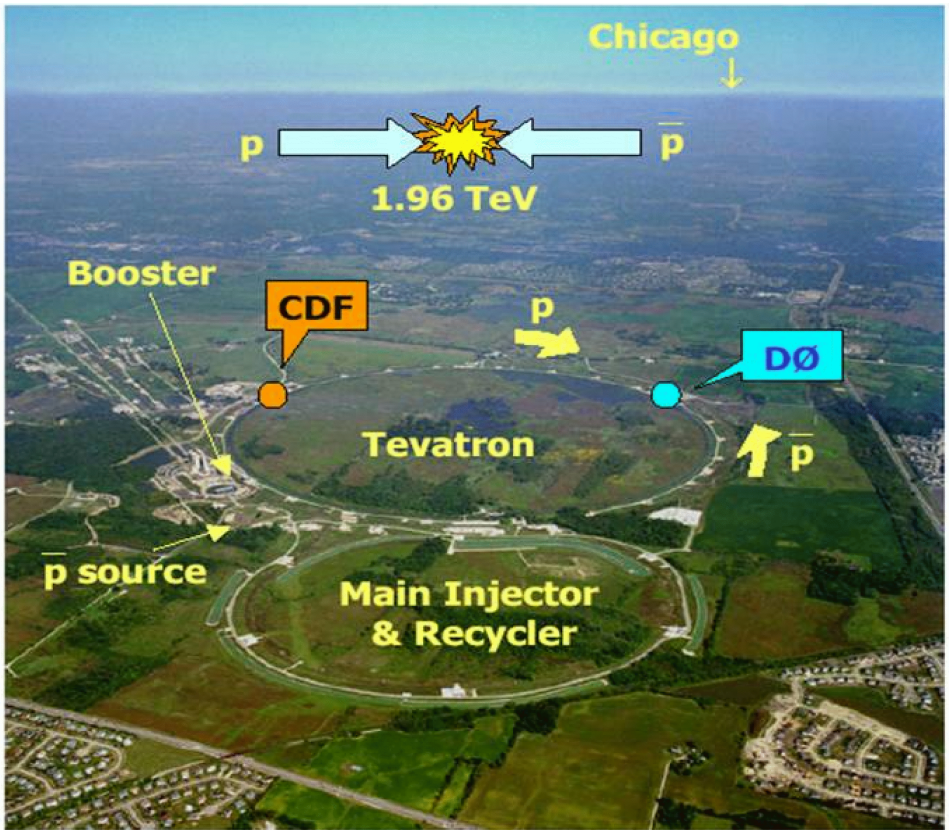
  (e.g. $p\bar{p} \to W^{\pm}Z^0 \to \ell^{\pm}\ell^+\ell^- + \not{E}_T$ similar to

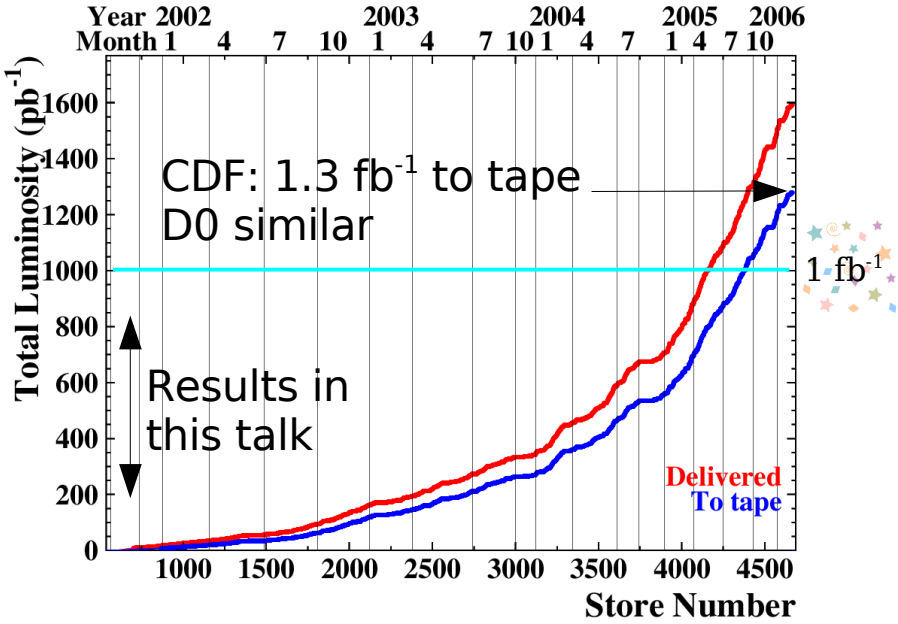
  $p\bar{p} \to \chi_2^{\pm}\chi_1^0 \to \ell^{\pm}\ell^+\ell^- + \not{E}_T$ SUSY signal)

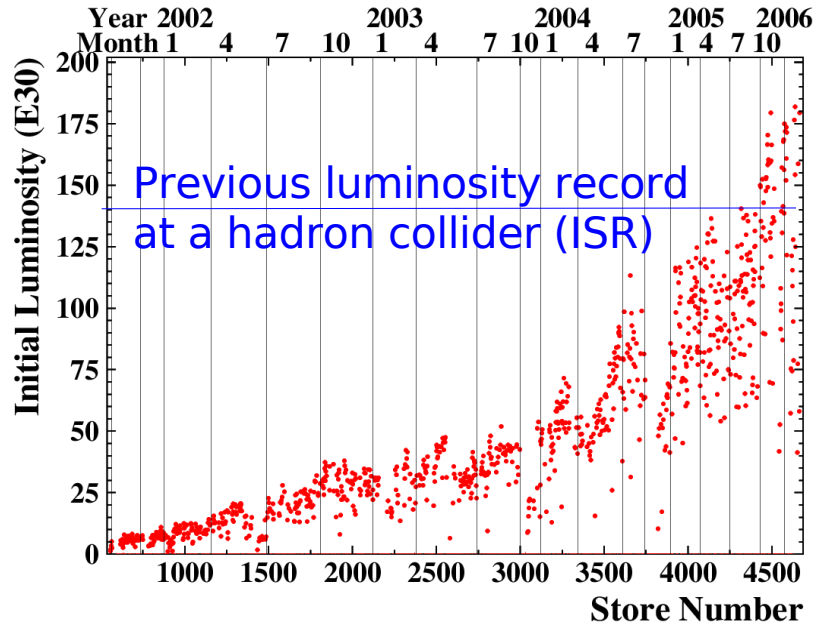


The Fermilab Tevatron

World's highest energy particle collider until turn-on of LHC @ CERN





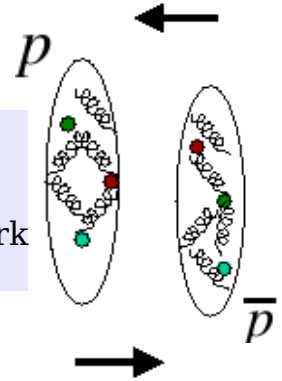


Run II Started 2001:

- $\sqrt{s}$=1.96 TeV
- record luminosity:
  $L_{inst} = 181.8 \times 10^{30}$ cm^{-2}s^{-1}
- $\int L\,dt = \sim 1.6$ fb^{-1}
  $\rightarrow$ 4 – 8 fb^{-1} expected by 2009

Collisions:

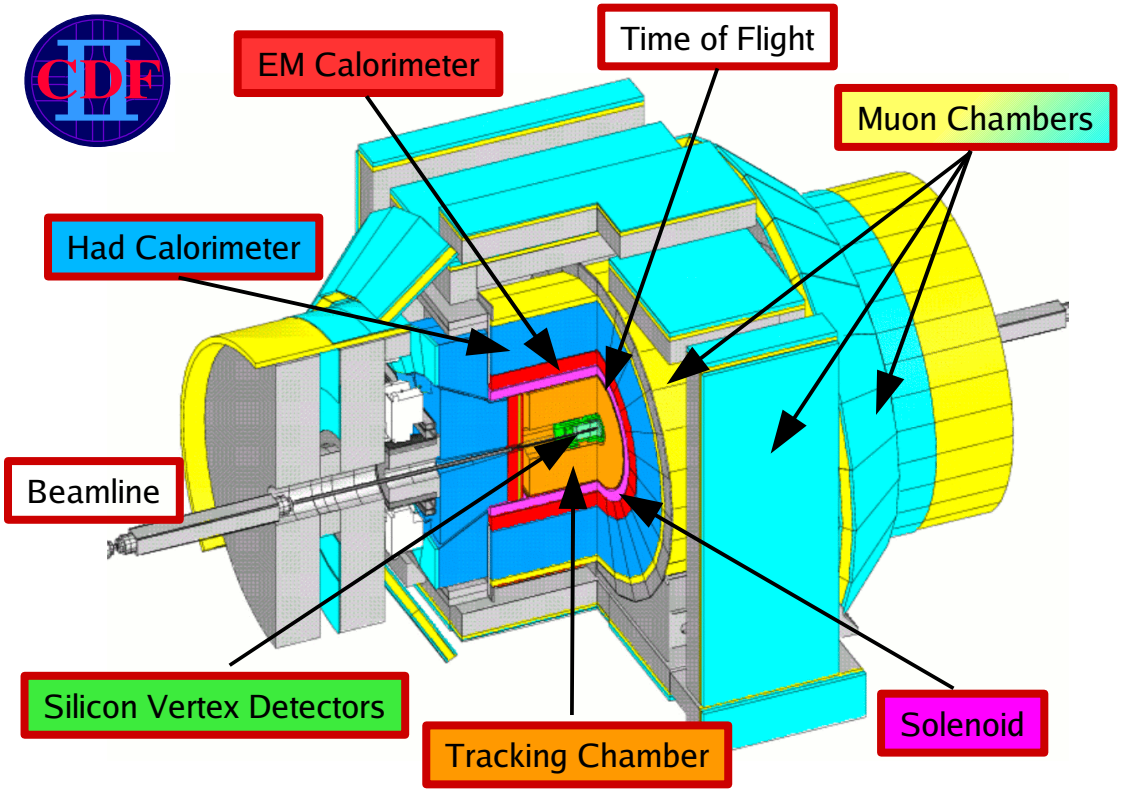
- gluon-gluon
- quark-antiquark
- gluon-quark

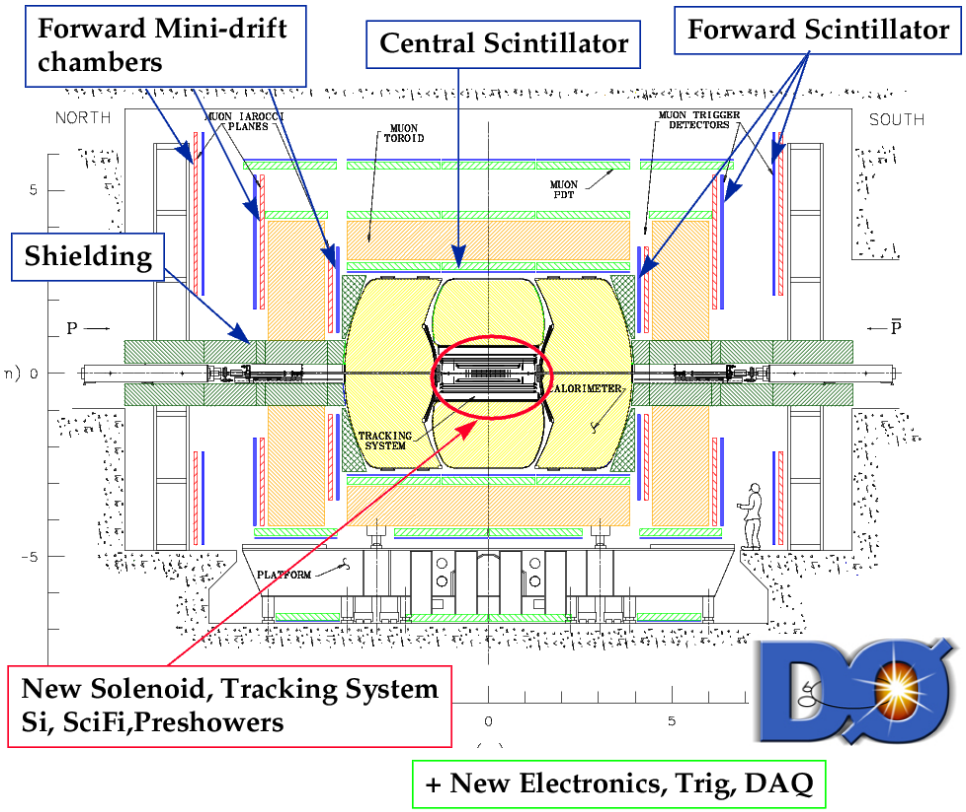


The Detectors: CDF and D0

Detectors upgraded for Run II for improvements in:

- Trigger & Data Acquisition
- Charged Particle Tracking
- Electron and muon coverage
- Particle identification





WWγ and WWZ Anomalous Couplings

Parameterize NP in terms of coupling parameters in an effective Lagrangian:

$$L_{WWV}/g_{WWV} = i\boxed{g_1^V}(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\boxed{\kappa_V}W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\boxed{\lambda_V}}{M_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu V^{\nu\lambda}$$

$V \equiv Z, \gamma$

Phys.Rev.D48 2182 (HISZ)

5 C and P conserving coupling parameters ($g_1^\gamma = 1$ by EM gauge invariance)

SM at tree level: $g_1^Z = k_Z = k_\gamma = 1, \quad \lambda_Z = \lambda_\gamma = 0$

$\Delta\kappa_Z = \Delta\kappa_\gamma = 0 \quad (\Delta\kappa \equiv \kappa - 1) \qquad \Delta g_1^Z = 0 \quad (\Delta g_1^Z \equiv g_1^Z - 1)$

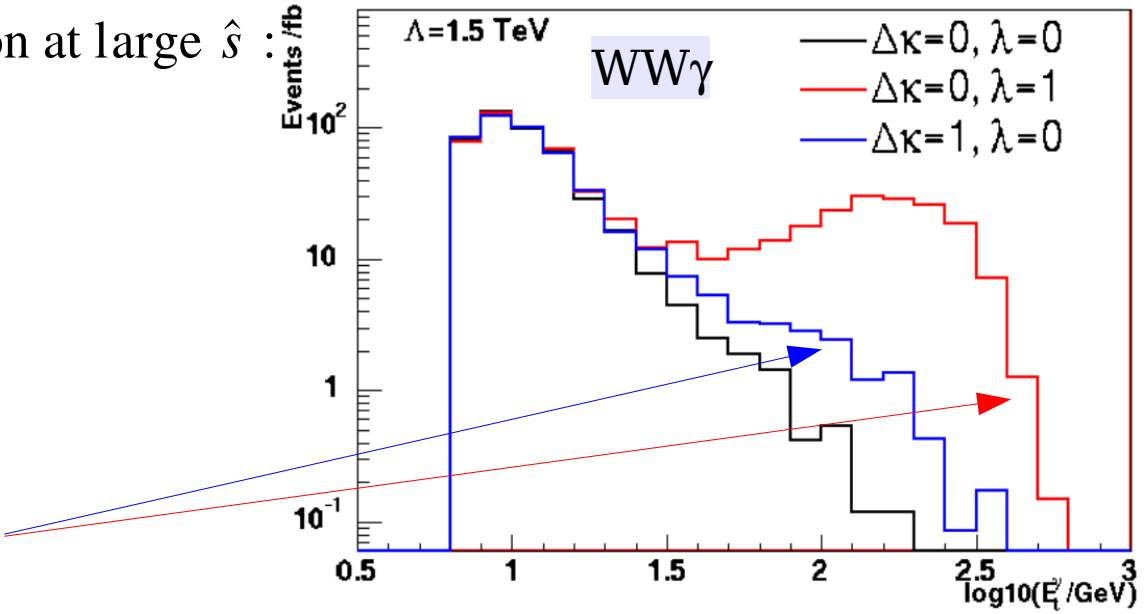
Form factor anzatz to avoid unitarity violation at large $\hat{s}$:

$$\alpha \Rightarrow \alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^2}$$

$\sqrt{\hat{s}}$ = CM energy of subprocess

Λ = scale of NP ~1 to 2 TeV

Anomalous couplings enhance cross-section at high gauge boson E_T



Wγ Production

W→ℓν selection:

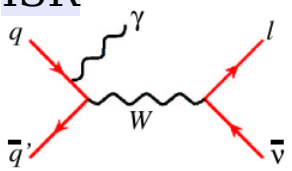
- Isolated high p_T(e,μ) ≳25 GeV
- $\not\!\!E_T$ ≳ 25 GeV
- 30 > M(ℓν) > 120 GeV

Photon selection:

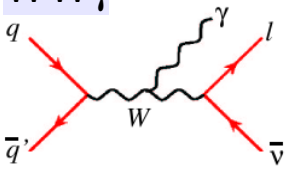
- |η| < 1.1 (central)
- ΔR(ℓ,γ) > 0.7

Main background from W+jet(s), where a jet fakes a photon

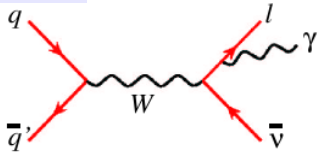
ISR



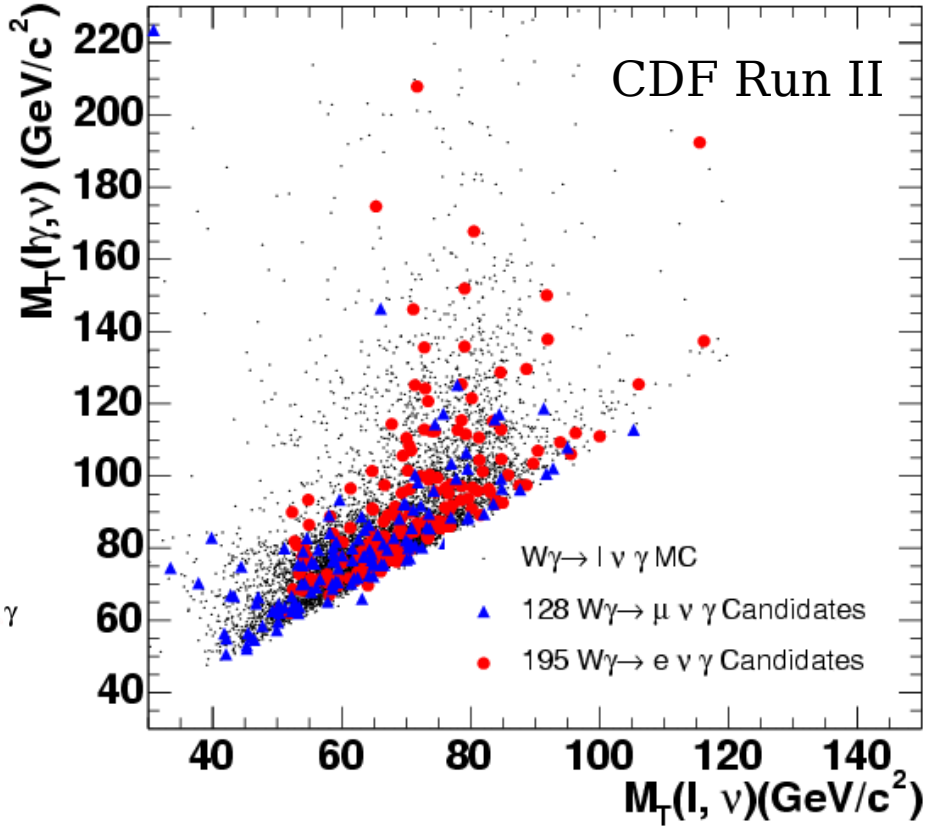
WWγ



FSR



3-body vs. 2-body mass



CDF ($\int L\,dt$ = 200 pb^{-1}, $E_t(\gamma)$ > 7 GeV):

$$\sigma(W\gamma)\times BR(W\to l\nu)=18.1\pm1.6(\text{stat})\pm2.4(\text{syst})\pm1.2(\text{lum})\ \text{pb}$$

PRL 94, 041803 (2005)

SM: 19.3 ± 1.4 pb

NLO: Baur,Han,Ohnemus 93/98

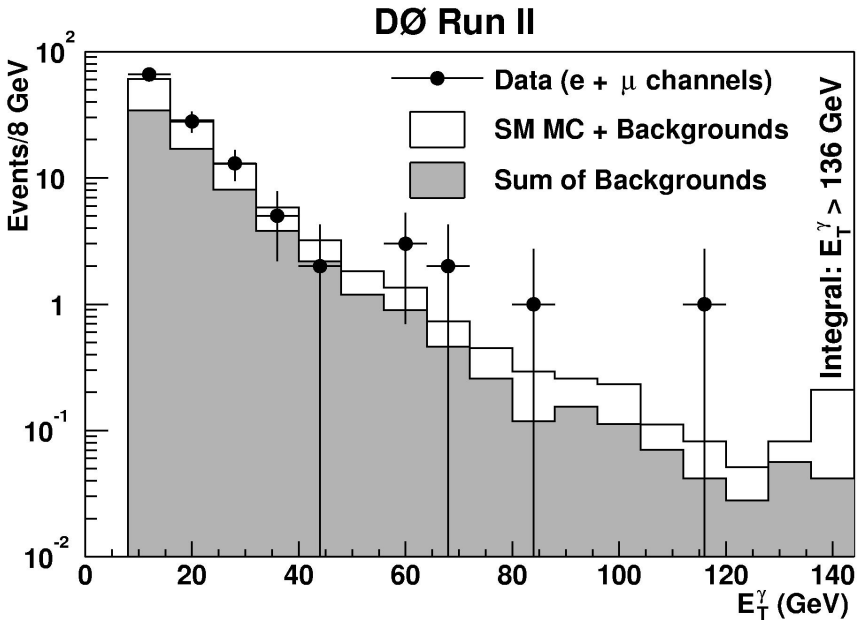
D0 ($\int L\,dt$ = 162 pb^{-1}, $E_t(\gamma)$ > 8 GeV):

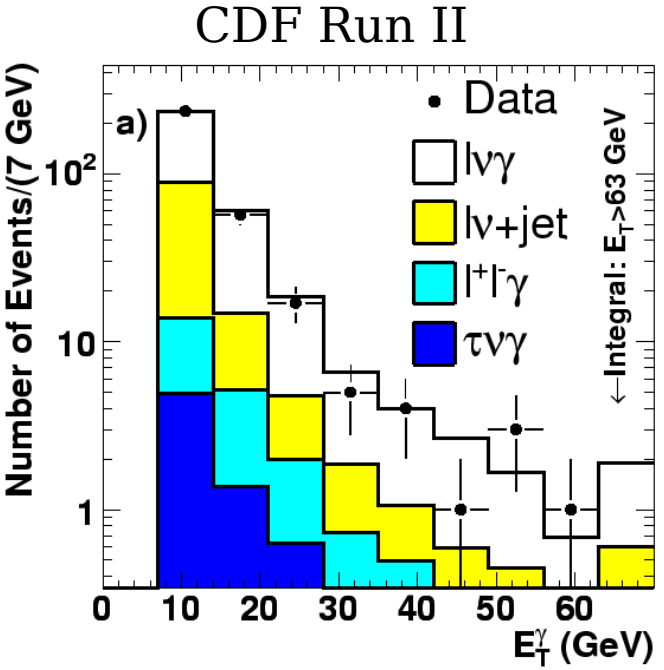
$$\sigma(W\gamma)\times BR(W\to l\nu)=14.8\pm1.6(\text{stat})\pm1.0(\text{syst})\pm1.0(\text{lum})\ \text{pb}$$

Phys.Rev D71 091108 (2005)

SM: 16.0 ± 0.4 pb

WWγ Anomalous Couplings

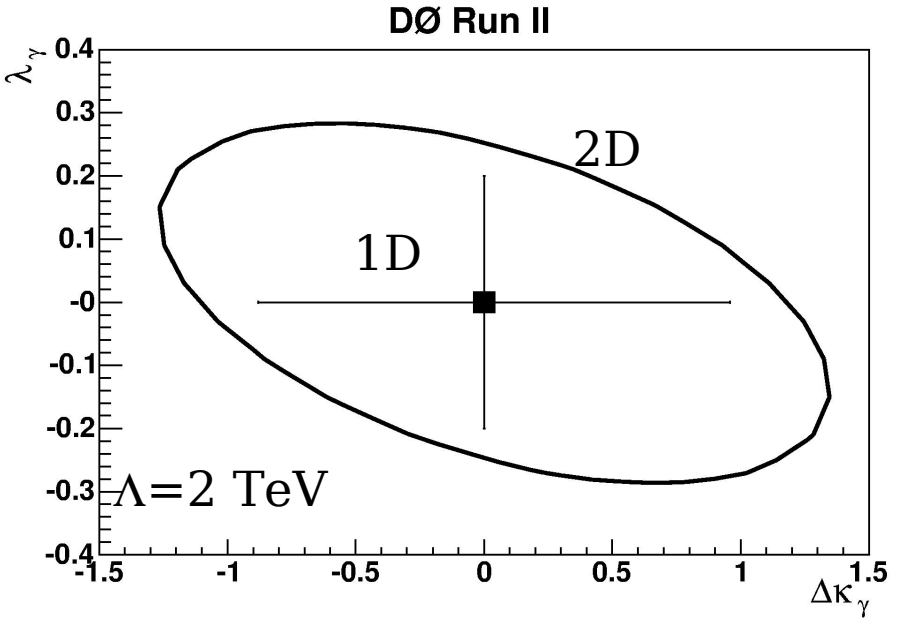




D0: limits for anomalous couplings:

1D limits at 95% CL

$$-0.88 < \Delta\kappa_\gamma < 0.96$$
$$-0.20 < \lambda_\gamma < 0.20$$



Zγ Production

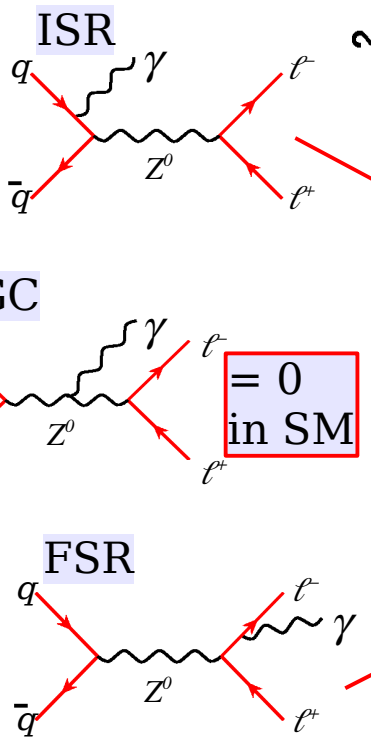
$Z \to \ell^+\ell^-$ selection:

- 2 Isolated high $p_T(e,\mu) \gtrsim 25$ GeV
- $40 > M(\ell^+\ell^-) > 130$ GeV

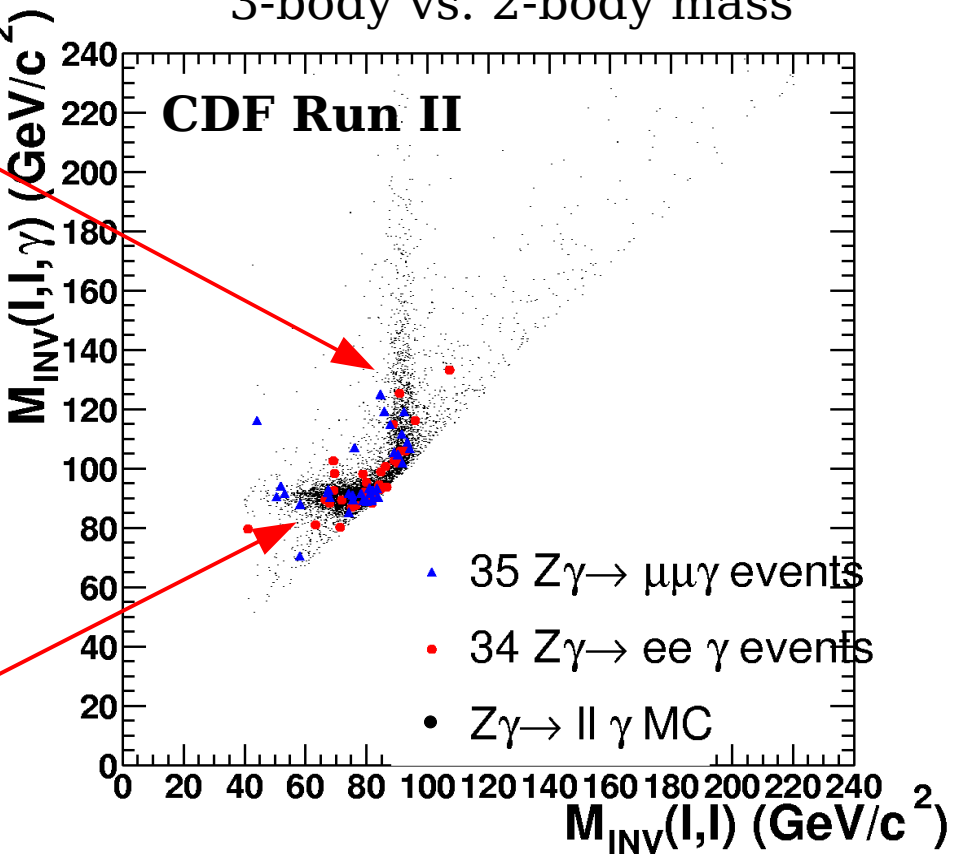
Photon selection:

- $|\eta| < 1.1$ (central)
- $\Delta R(\ell,\gamma) > 0.7$

Main background from Z+jet(s), where a jet fakes a photon



3-body vs. 2-body mass



CDF ($\int L\,dt = 200$ pb^{-1}, $E_t(\gamma) > 7$ GeV):

$$\sigma(Z\gamma)\times BR(Z\to ll) = 4.6 \pm 0.5\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.3\,(\text{lum})\ \text{pb}$$

PRL 94, 041803 (2005)

SM: 4.5 ± 0.3 pb

NLO: Baur,Han,Ohnemus 93/98

D0 ($\int L\,dt = 300$ pb^{-1}, $E_t(\gamma) > 8$ GeV):

$$\sigma(Z\gamma)\times BR(Z\to ll) = 4.2 \pm 0.4\,(\text{stat+syst}) \pm 0.3\,(\text{lum})\ \text{pb}$$

PRL 95, 051802 (2005)

SM: 3.9 ± 0.2 pb

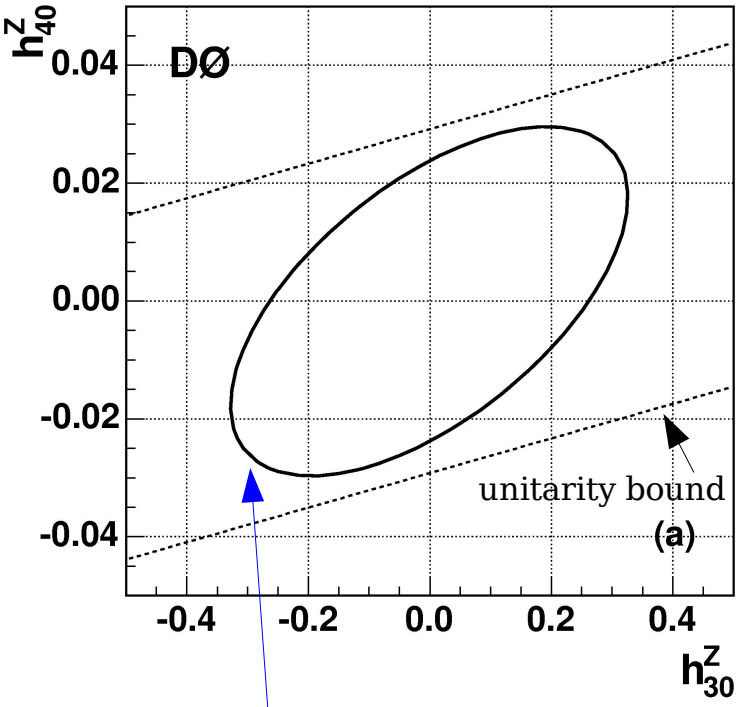
ZZγ and Zγγ Anomalous Couplings

Non-SM characterized by an effective Lagrangian with 8 form-factor coupling parameters:
h_1^V, h_2^V, h_3^V, and h_4^V (V = γ or Z)

Baur, Berger, Phys.Rev. D47 (1993) 4889

CP violating h_1^V and h_2^V
CP conserving h_3^V and h_4^V

SM: all couplings = 0

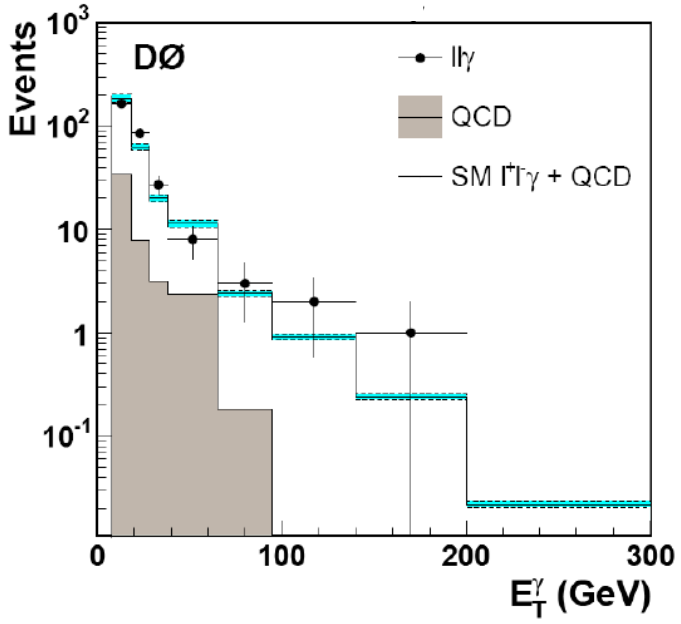


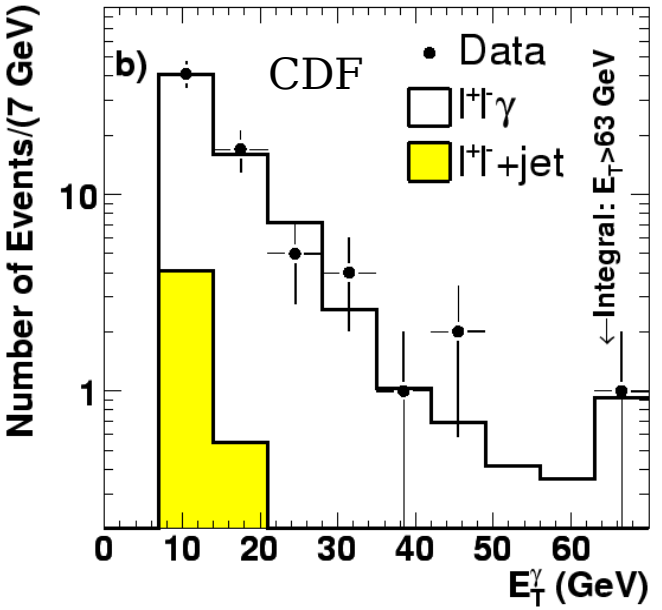
ZZγ limits 2D at 95%CL

Zγγ limits nearly identical

D0 1-d limits
(Λ = 1 TeV)

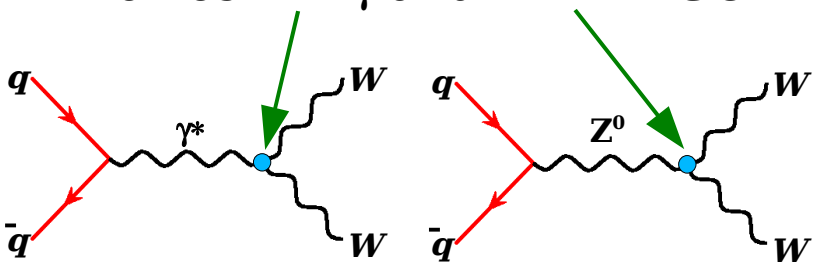
$$|h_{10,30}^{\gamma}| < 0.23$$
$$|h_{20,40}^{\gamma}| < 0.019$$
$$|h_{10,30}^{Z}| < 0.23$$
$$|h_{20,40}^{Z}| < 0.020$$



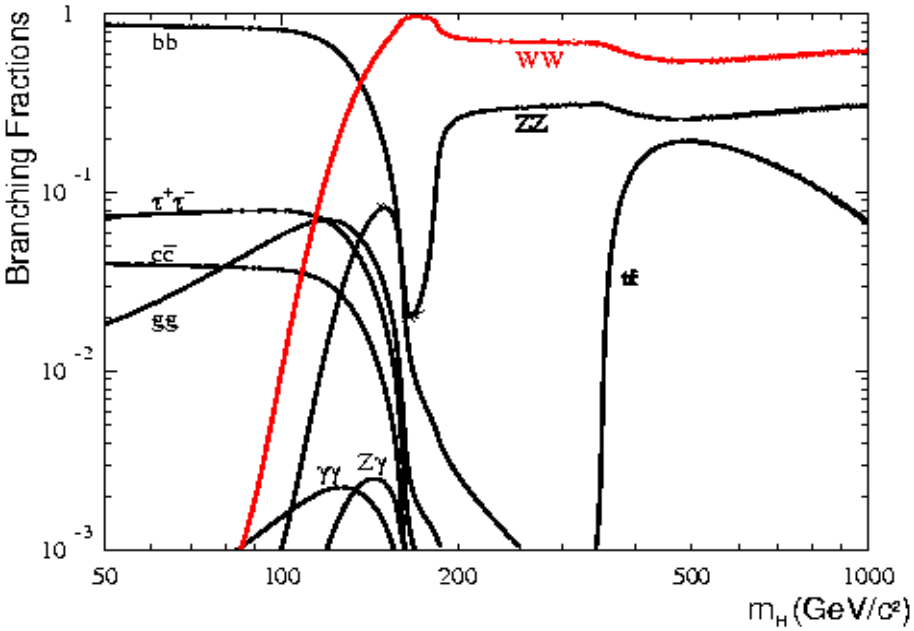


WW Production

Involves WWγ and WWZ TGC



Same final state in Higgs decay channel



NLO cross section: 12.4 ± 0.8 pb

Campbell,Ellis, Phys.Rev. D60 (1999) 113006

Previous Run II measurements:

CDF: $\int L\,dt = 184\ pb^{-1}$

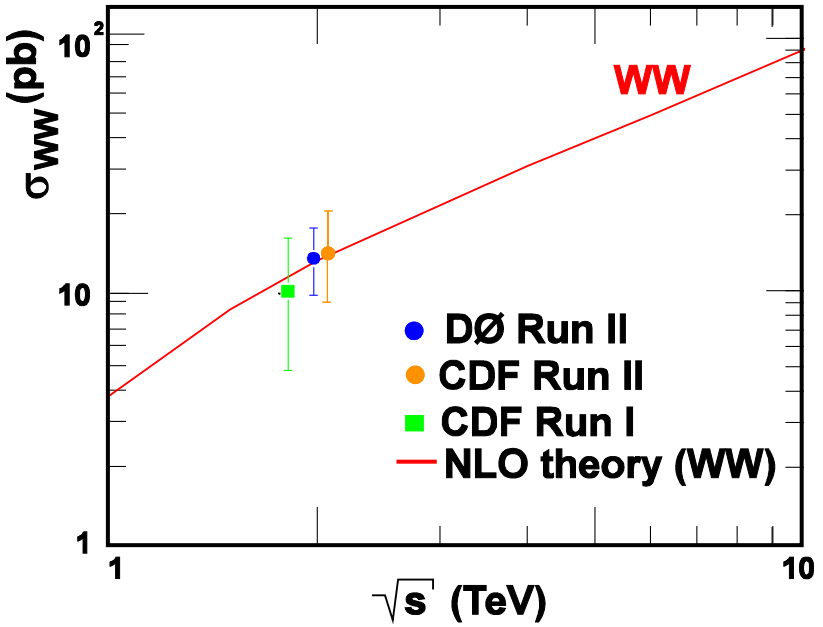
Observe 17 with expected background of 5.0 events PRL 94 (2005) 211801

$$\sigma = 14.6^{+5.8}_{-5.1}(stat)^{+1.8}_{-3.0}(syst) \pm 0.9(lum)\ pb$$

D0: $\int L\,dt = 240\ pb^{-1}$

Observe 25 with expected background of 8.1 events PRL 94 (2005) 151801

$$\sigma = 13.8^{+4.3}_{-3.8}(stat)^{+1.2}_{-0.9}(syst) \pm 0.9(lum)\ pb$$



WW Cross Section

New measurement from CDF using $\int L\,dt = 825\ pb^{-1}$

$WW \rightarrow \ell^+\ell^- + \not\!\!E_T$ selection:

- Two OS leptons (e,μ) with $p_T > 20$ GeV
- Z veto ($76 < M_{\ell+\ell-} < 106$ GeV) if $\not\!\!E_T/\sqrt{(\Sigma E_T)} < 3$ for ee, μμ
- $\not\!\!E_T > 25$ GeV
- $\Delta\phi(\ell, \not\!\!E_T) > 20°$ if $25 < \not\!\!E_T < 50$ GeV
- # jets ($E_T > 15$ GeV and $|\eta| < 2.5$) = 0

New!

Mode	ee	$e\mu$	$\mu\mu$	ll
WW	$12.82 \pm 0.06 \pm 1.06$	$28.82 \pm 0.09 \pm 2.39$	$10.71 \pm 0.05 \pm 0.89$	$52.36 \pm 0.12 \pm 4.35$
Drell-Yan	$4.96 \pm 0.52 \pm 1.29$	$3.85 \pm 0.44 \pm 1.00$	$3.03 \pm 0.38 \pm 0.79$	$11.84 \pm 0.78 \pm 3.08$
$t\bar{t}$	$0.05 \pm 0.01 \pm 0.01$	$0.11 \pm 0.01 \pm 0.01$	$0.04 \pm 0.01 \pm 0.00$	$0.20 \pm 0.01 \pm 0.02$
$WZ + ZZ$	$3.62 \pm 0.02 \pm 0.36$	$0.93 \pm 0.01 \pm 0.09$	$3.39 \pm 0.01 \pm 0.34$	$7.93 \pm 0.02 \pm 0.79$
$W\gamma$	$3.57 \pm 0.12 \pm 0.71$	$3.25 \pm 0.10 \pm 0.65$	$0.02 \pm 0.01 \pm 0.00$	$6.83 \pm 0.16 \pm 1.37$
W+jets	$2.96 \pm 0.23 \pm 0.71$	$6.69 \pm 0.41 \pm 1.98$	$1.33 \pm 0.17 \pm 0.53$	$10.99 \pm 0.50 \pm 3.20$
Sum Bkg	$15.16 \pm 0.59 \pm 1.68$	$14.83 \pm 0.61 \pm 2.31$	$7.81 \pm 0.42 \pm 1.01$	$37.79 \pm 0.94 \pm 4.71$
Expected	$27.98 \pm 0.59 \pm 1.99$	$43.65 \pm 0.61 \pm 3.33$	$18.52 \pm 0.42 \pm 1.34$	$90.15 \pm 0.95 \pm 6.41$
Data	29	47	19	95

Expect:

37.8 ± 4.8 background events

Observe:

95 events

$$\sigma(p\bar{p} \rightarrow WW) = 13.6 \pm 2.3\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 1.2\,(\text{lum})\ \text{pb}$$

Most precise single measurement from Tevatron

$WW \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu$ Candidate

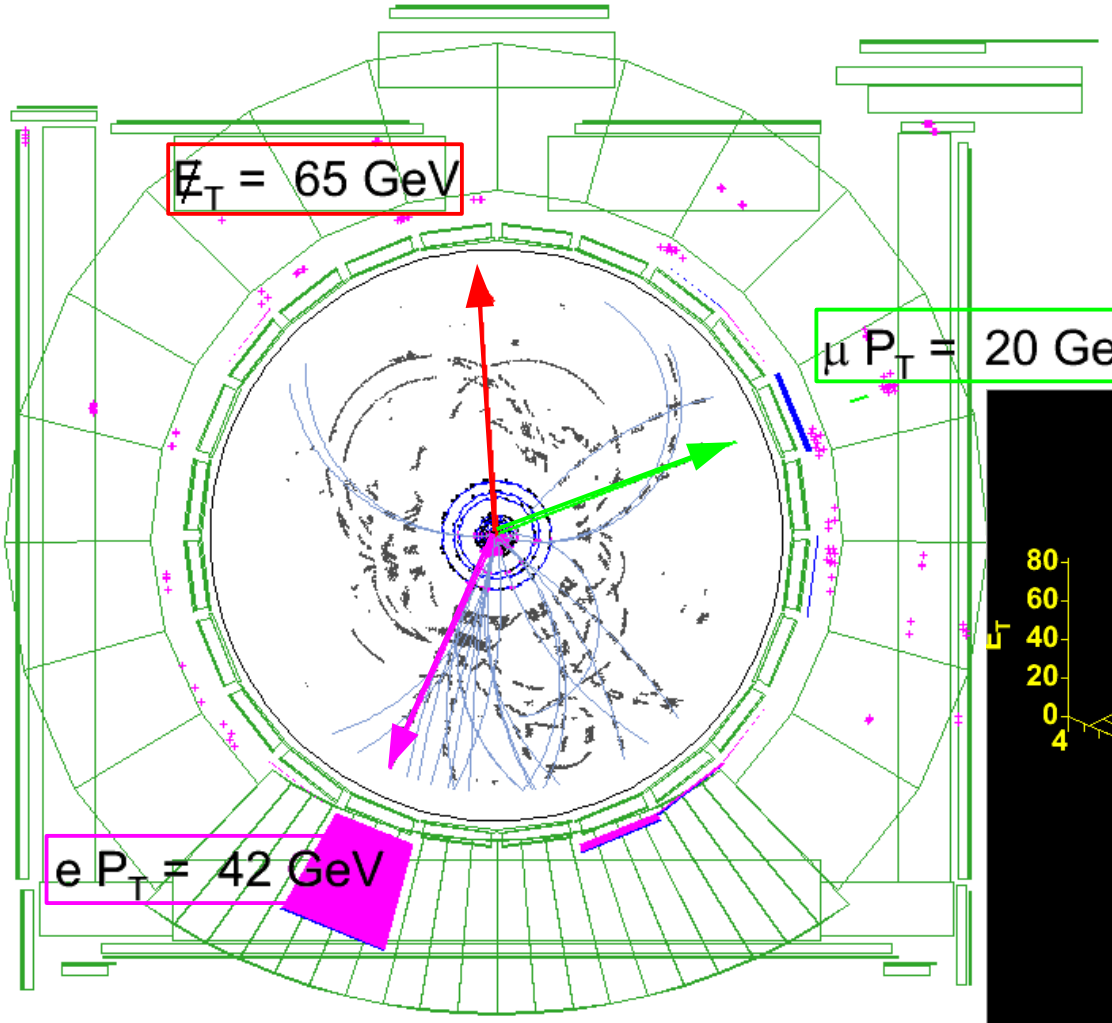
eμ channel low background: S/B ~ 3

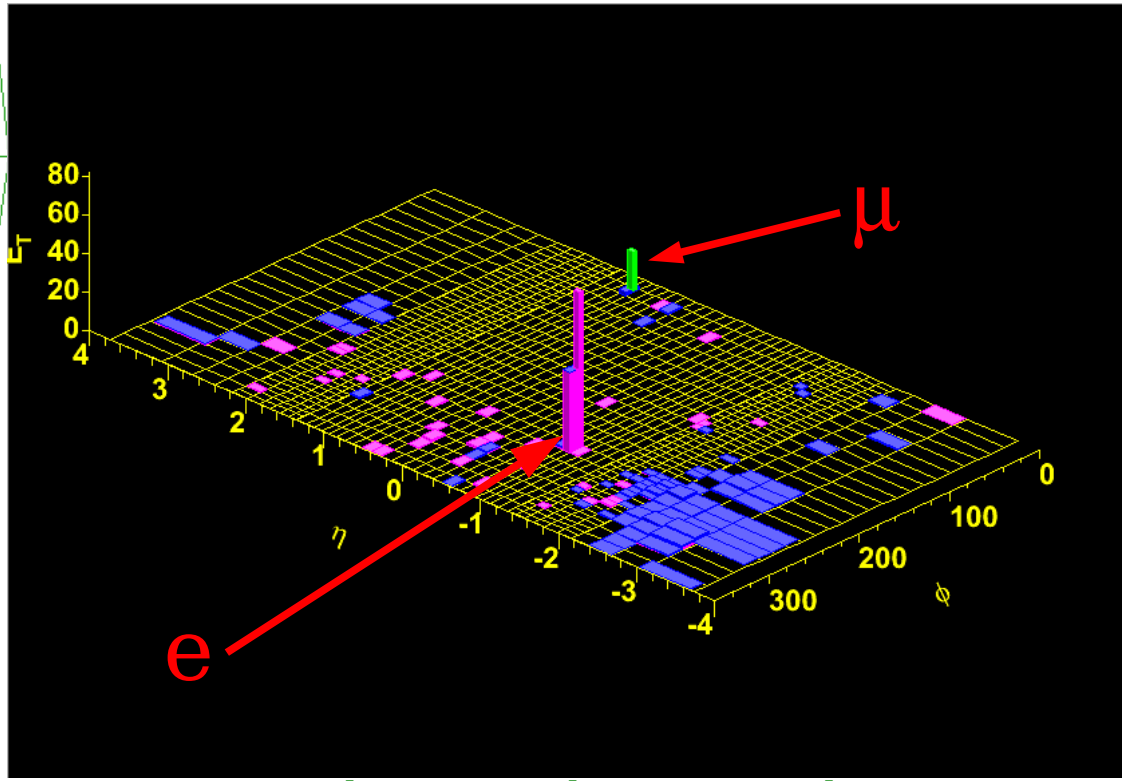
$\Delta\Phi_{min}(\ell, \not{E}_T) = 74^o$

$M_{\ell\ell} = 81.9$ GeV/c^2

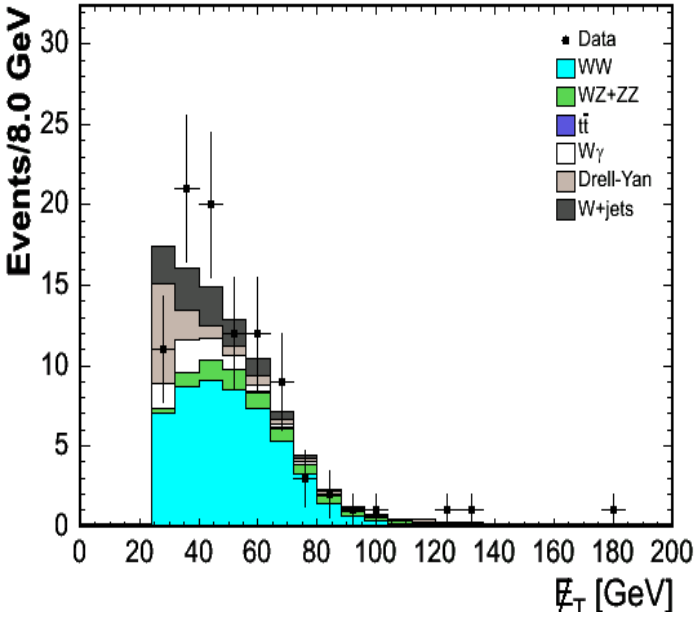
$\not{E}_t/\sqrt{(\Sigma E_t)} = 6.1$

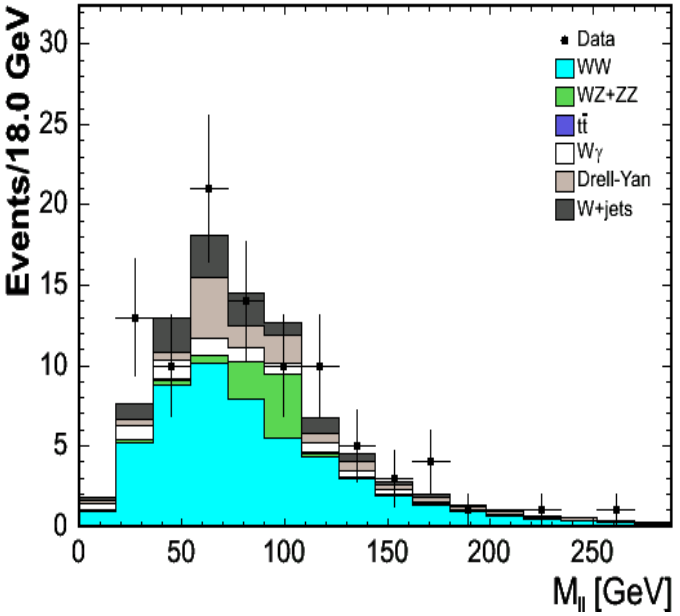
$\Sigma E_T = 113$ GeV

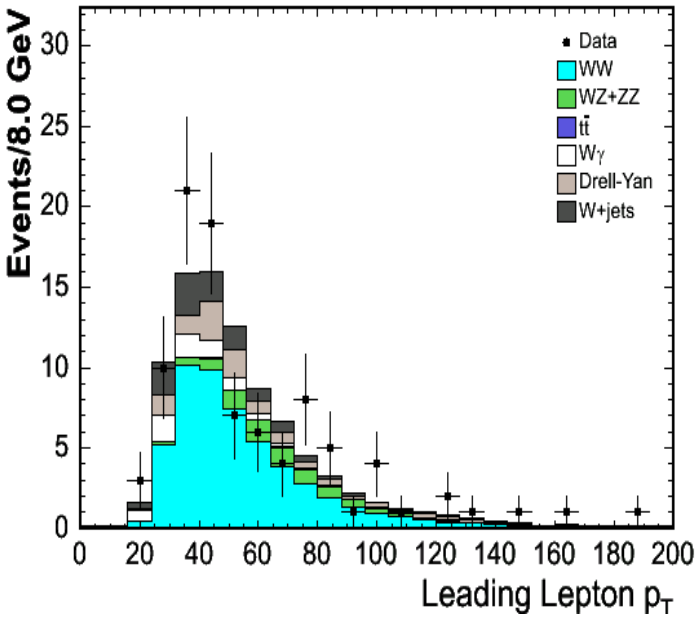




Some WW Kinematic Distributions







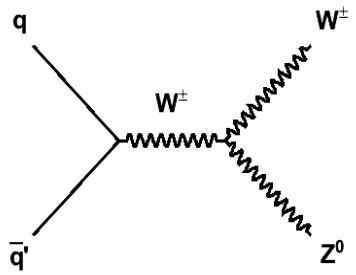
With ~57 WW pairs:

Just observing WW signal

Exploit WW kinematics
in search of Higgs,NP!

WZ Production

Involves a single triple gauge coupling:



- Not available @ LEP
- Measure WWZ coupling independent of WWγ
- WZ→ trileptons rare but distinct signature
- Not been conclusively observed

NLO cross section: 3.7 ± 0.1 pb

Campbell,Ellis, Phys.Rev. D60 (1999) 113006

CDF (WZ+ZZ): $\int L\,dt$ = 194 pb^{-1}

Observe 3 events (2ee, 1μμ) with expected background of 1.0±0.2 and signal of 2.3±0.3 in 2,3, and 4 lepton final states

Phys.Rev. D71, 091105

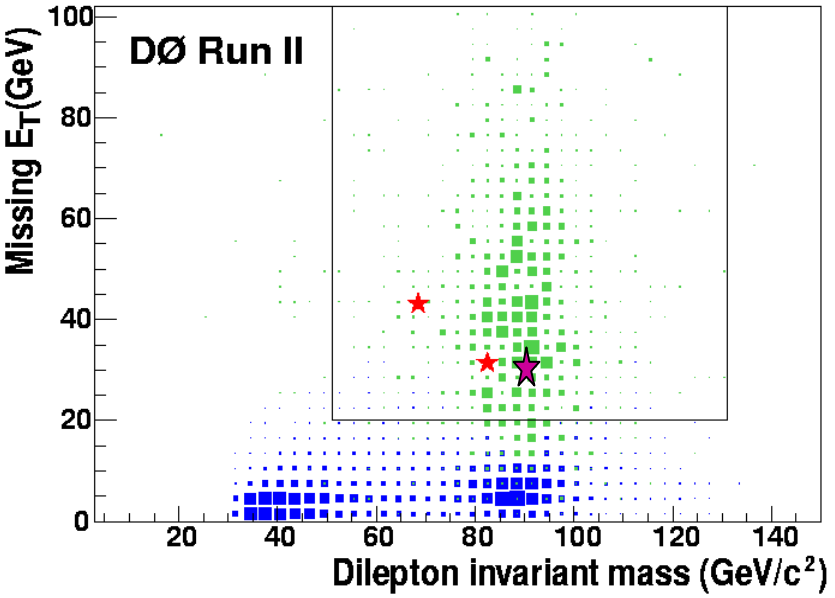
$\sigma < 15.2\,\text{pb}$ @ 95 C.L (SM: $5.0 \pm 0.4\,\text{pb}$)

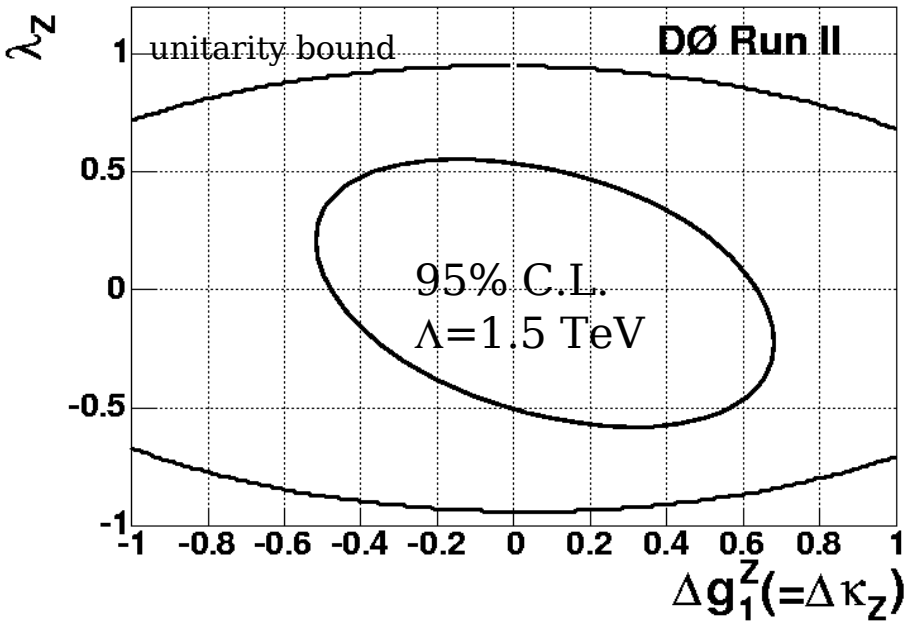
D0 (WZ): $\int L\,dt$ = 300 pb^{-1}

Observe 3 events (1eee, 2μμμ) with expected background of 0.71±0.08 and signal of 2.0±0.2 in 3 lepton final state

PRL 95, 141802 (2005)

$\sigma < 13.3\,\text{pb}$ @ 95 C.L $\quad \sigma = 4.5^{+3.8}_{-2.6}\,(\text{stat+syst})\,\text{pb}$





$W^{\pm}Z^{0} \rightarrow \ell^{\pm}\ell^{+}\ell^{-} + \not\!\!E_T$

New from CDF using $\int L\,dt = 825\ pb^{-1}$

$W^{\pm}Z^{0} \rightarrow \ell^{\pm}\ell^{+}\ell^{-} + \not\!\!E_T$ selection:

- 3 leptons (e,μ) with Pt > 20,10,10 GeV
- Z region (76 < Mll < 106)
- $\not\!\!E_T$ > 25 GeV

Observe 2 events with expected background of 0.9±0.2 and signal of 3.7±0.3

σ(WZ) < 6.34 pb (95% C.L.)

New!

Signal:

WZ: 3.72 ± 0.02 (stat.) ± 0.15 (syst.)

Backgrounds:

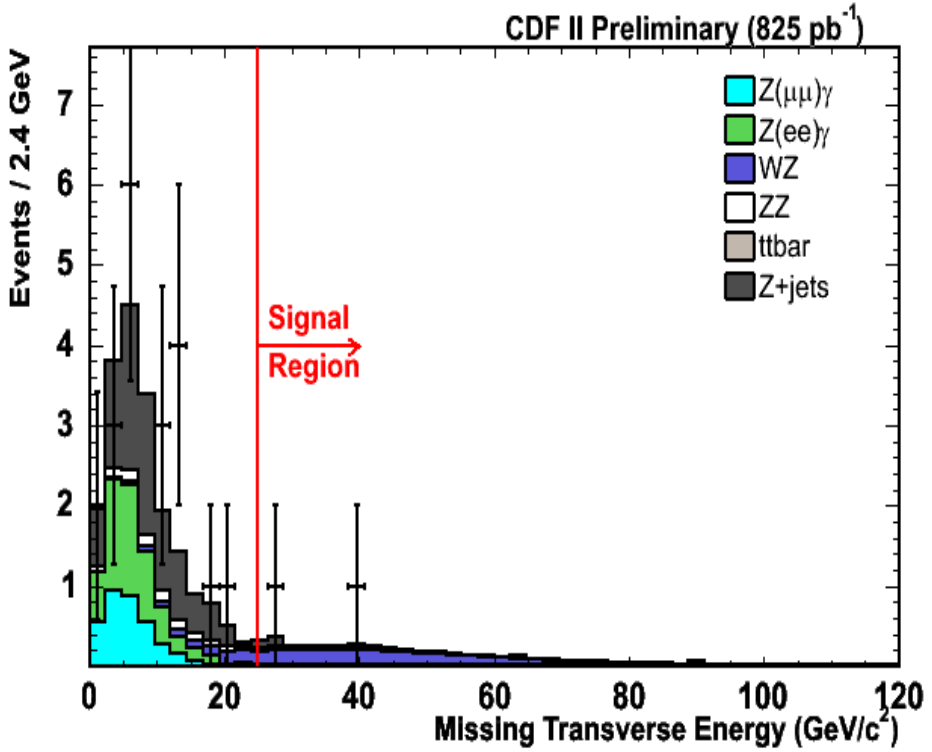
ZZ: 0.50 ± 0.01 (stat.) ± 0.05 (syst.)

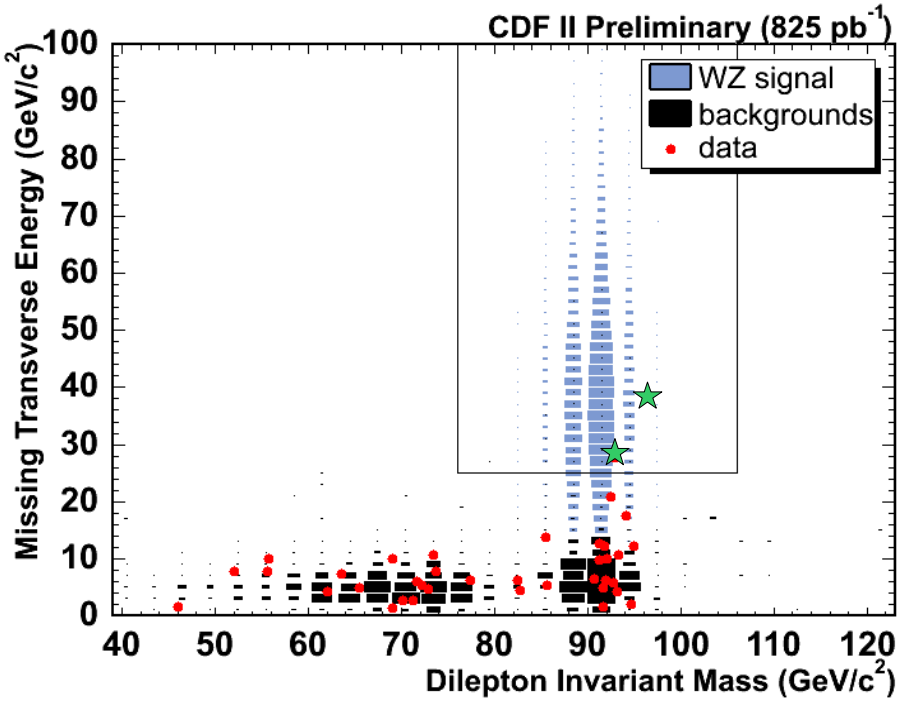
Zγ: 0.03 ± 0.01 (stat.) ± 0.01 (syst.)

$t\bar{t}$: 0.05 ± 0.01 (stat.) ± 0.01 (syst.)

Z+jets: 0.34 ± 0.07 (stat.) $^{+0.15}_{-0.09}$ (syst.)

Total: 0.92 ± 0.07 (stat.) $^{+0.16}_{-0.10}$ (syst.)



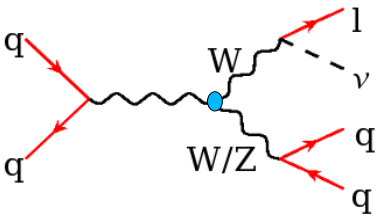


WW/WZ→ℓνjj

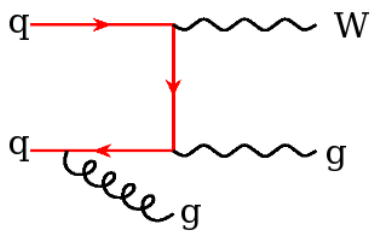
Pro: much larger branching fraction
Con: much larger backgrounds,
mainly from W+jets

- Isolated high $p_T(e,\mu) \gtrsim 25$ GeV
- $\not\!\!E_T > 25$ GeV.
- At least 2 jets $E_T > 15$ GeV
- Dijet mass 32-184 GeV

New!

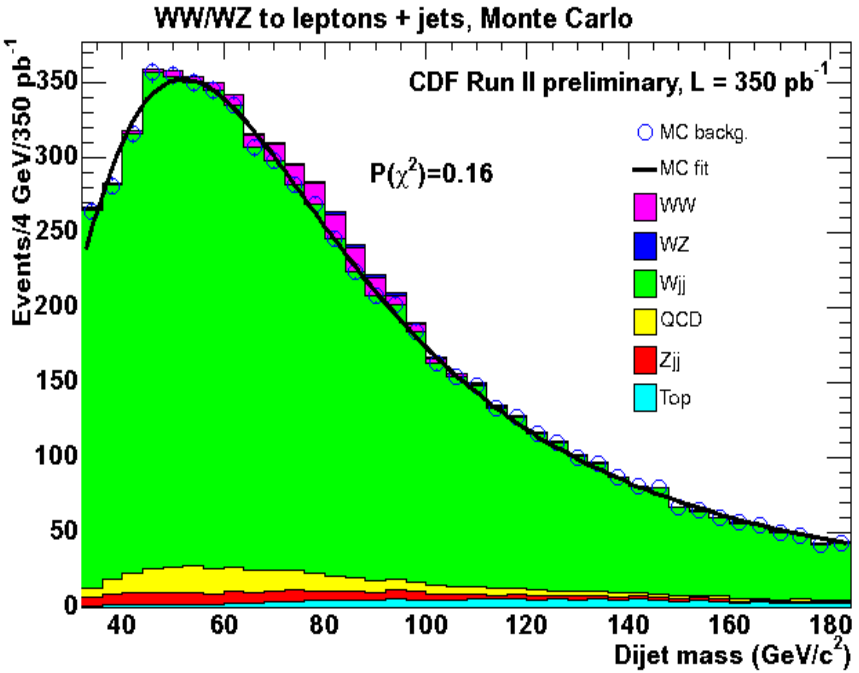


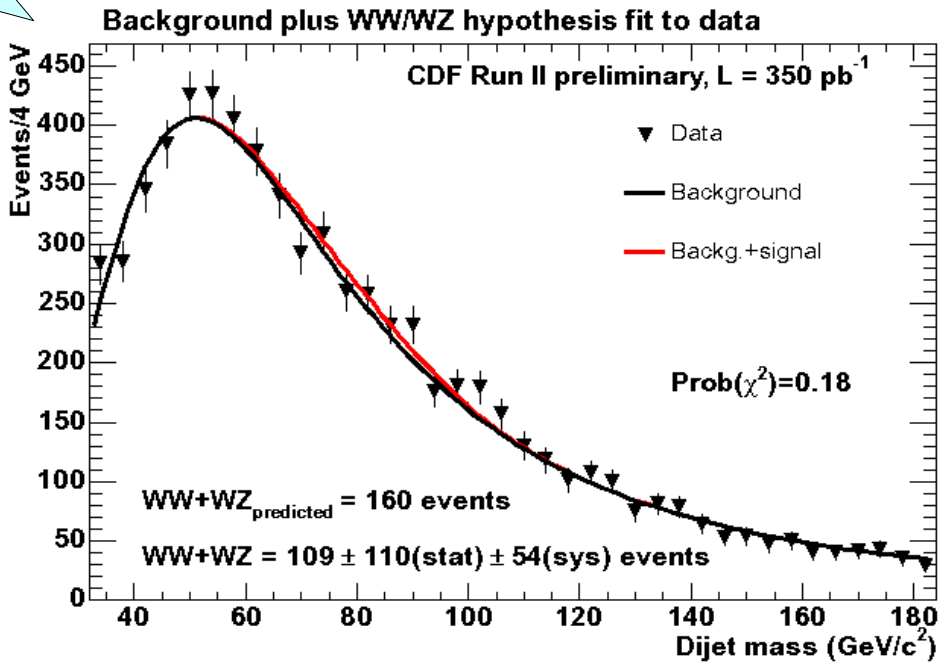
WW/WZ TGC diagram



Example W+2j diagram

★ Fit signal and background di-jet mass shape to data.

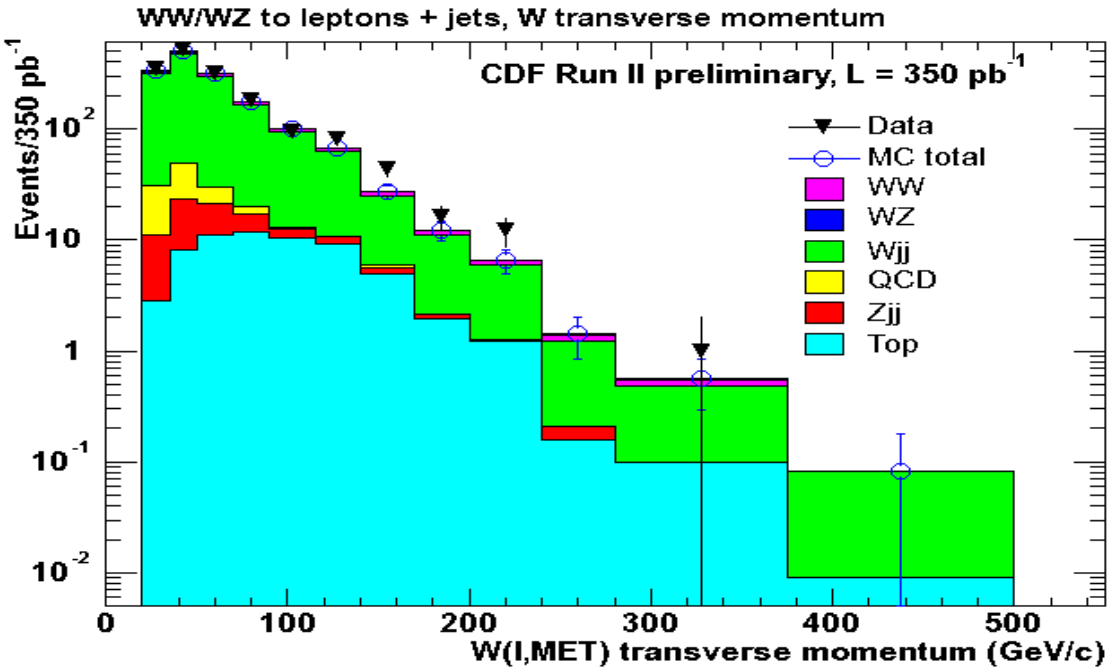


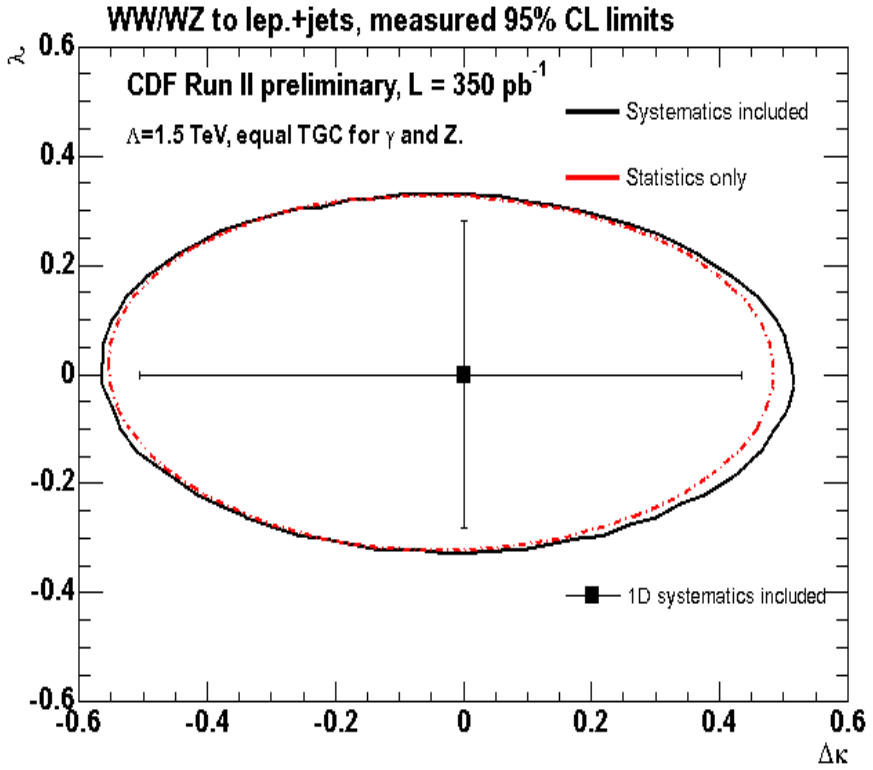


σ(WW+WZ) < 36 pb (95% C.L.)

Anomalous Couplings: WW/WZ→ℓνjj

- W p_T found to be most sensitive for anomalous coupling limits
- W p_T formed using lepton p_T and $\not\!\!E_T$ (ν)
- Full spectrum fit for AC hypothesis and used in setting limits





Determined 1D 95% C.L. limits:

$(\Delta\kappa,\lambda)$=([-0.51,0.44],[-0.28,0.28])

Summary/Outlook

Diboson production studied in:

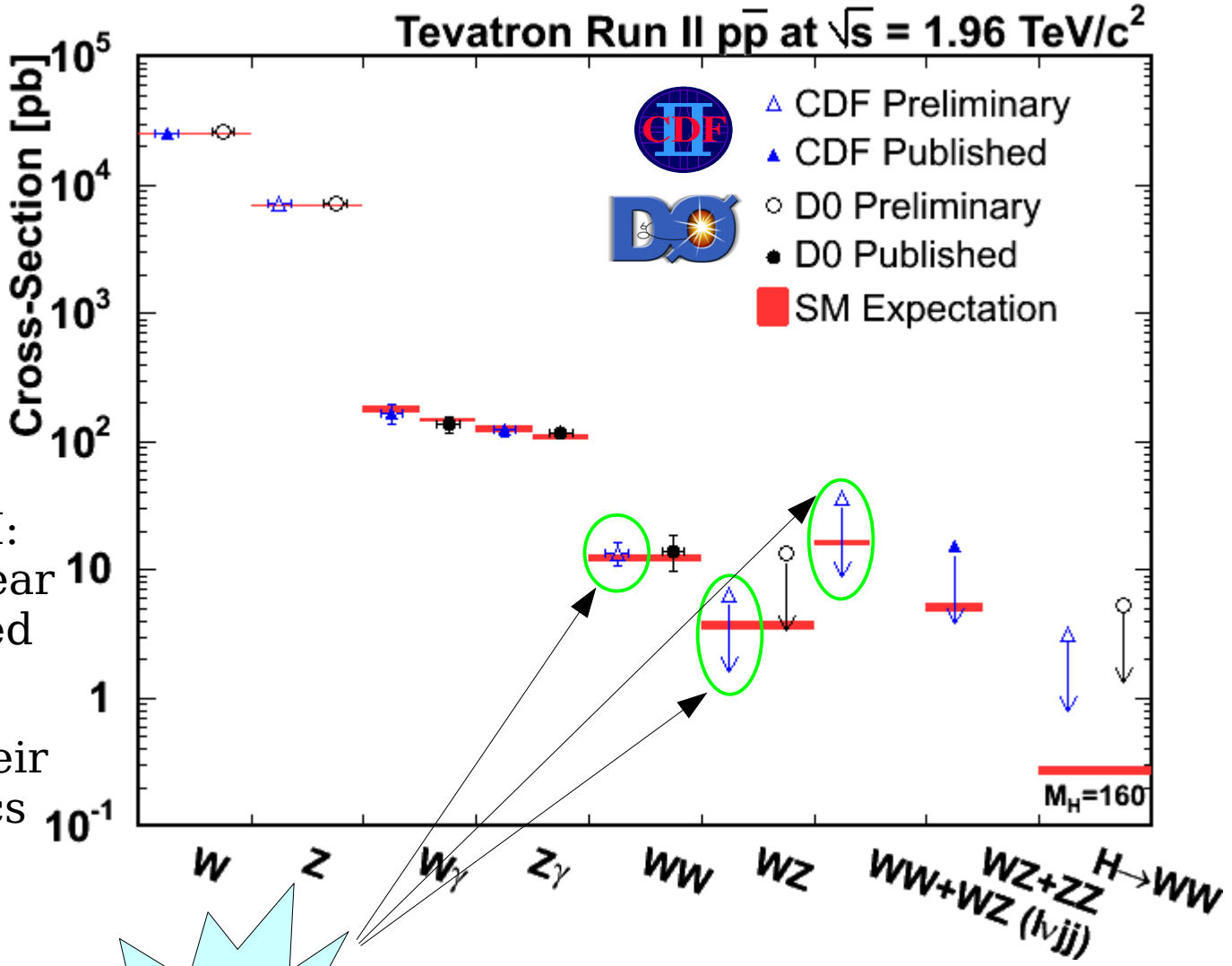
- WW
- WZ/ZZ
- Wγ
- Zγ

mainly in leptonic decay channels, but also final states with jets

- Results consistent with SM: Limits on anomalous trilinear gauge couplings determined
  → more on the way
- Dibosons interesting on their own in studying EWK physics

but...

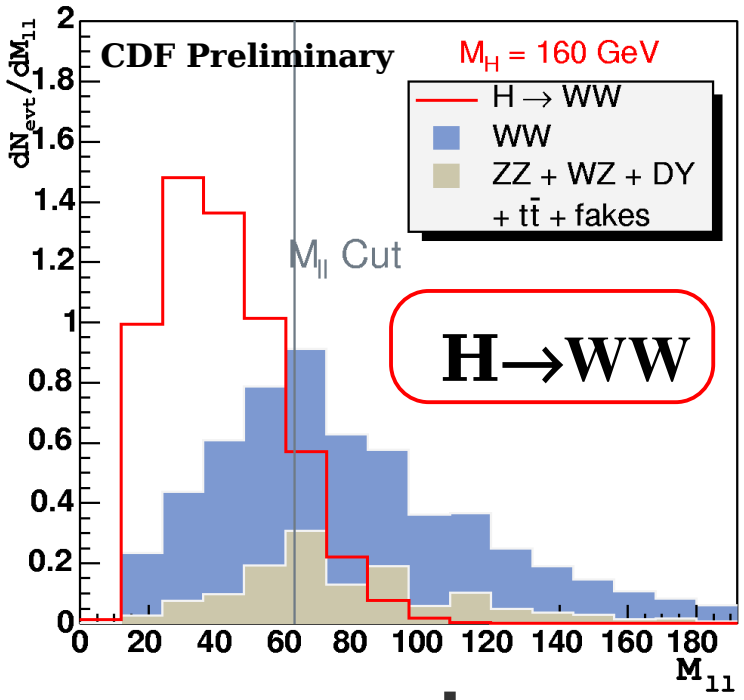
Looking forward to future diboson results (w/ 1fb^{-1}++) aiding in the search for Higgs and possible NP



New!

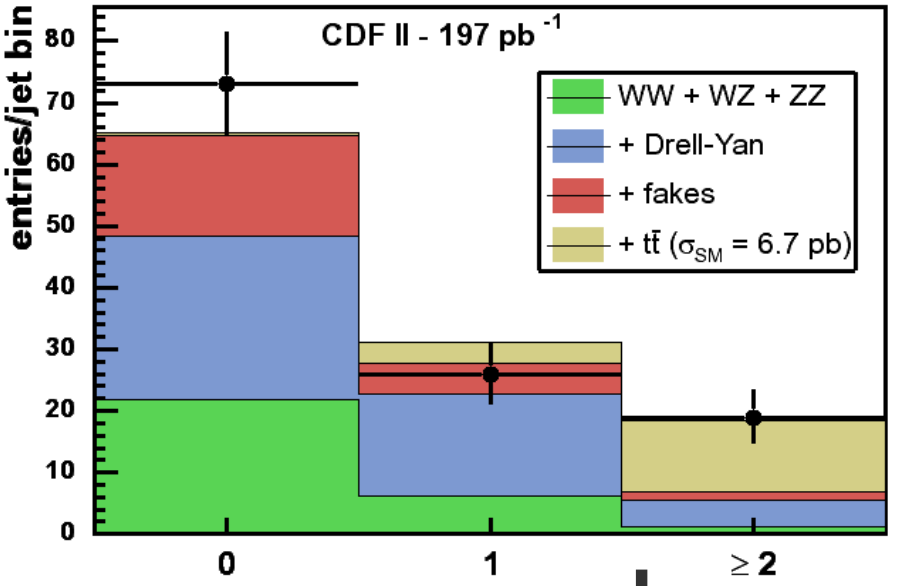
Extras

Dibosons: Everyone Else's Background

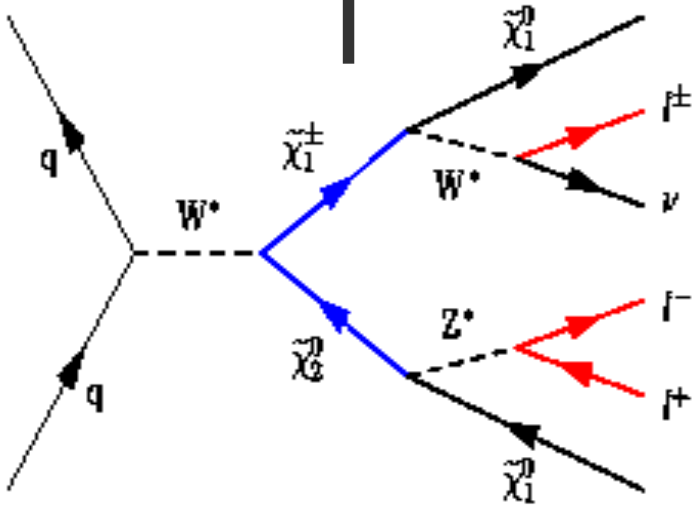


H→WW

$\bar{t}\bar{t}$→WW$\bar{b}\bar{b}$



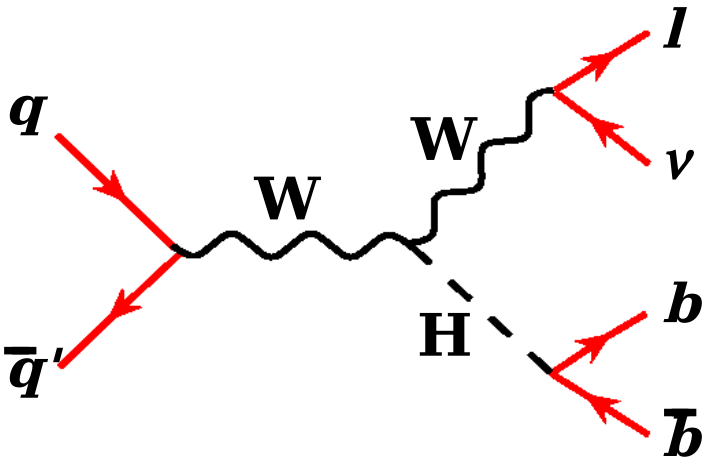
irreducible **reducible**



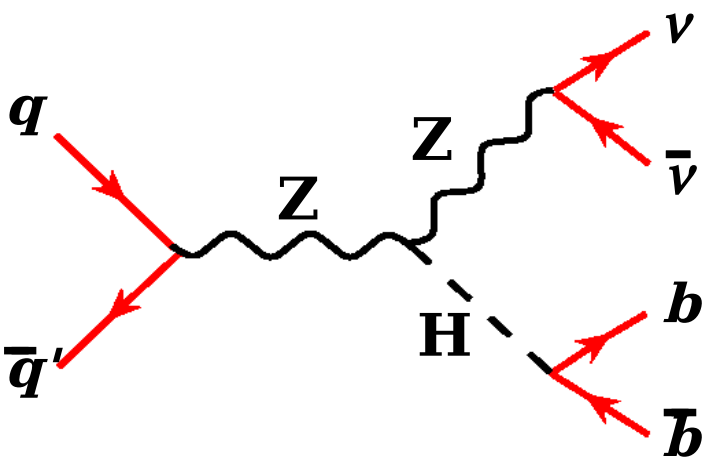
SUSY/EXOTICA

Relevance to Light Higgs Searches

$$p\,\bar{p} \to WH \to l\,\nu\,b\,\bar{b}$$



$$p\,\bar{p} \to ZH \to \nu\,\bar{\nu}\,b\,\bar{b}$$



$\sigma(WH;\ m_H = 115\ \text{GeV}) \approx 0.2$ pb

$\sigma(WZ) \times BR(Z \to b\bar{b}) \approx 0.6$ pb

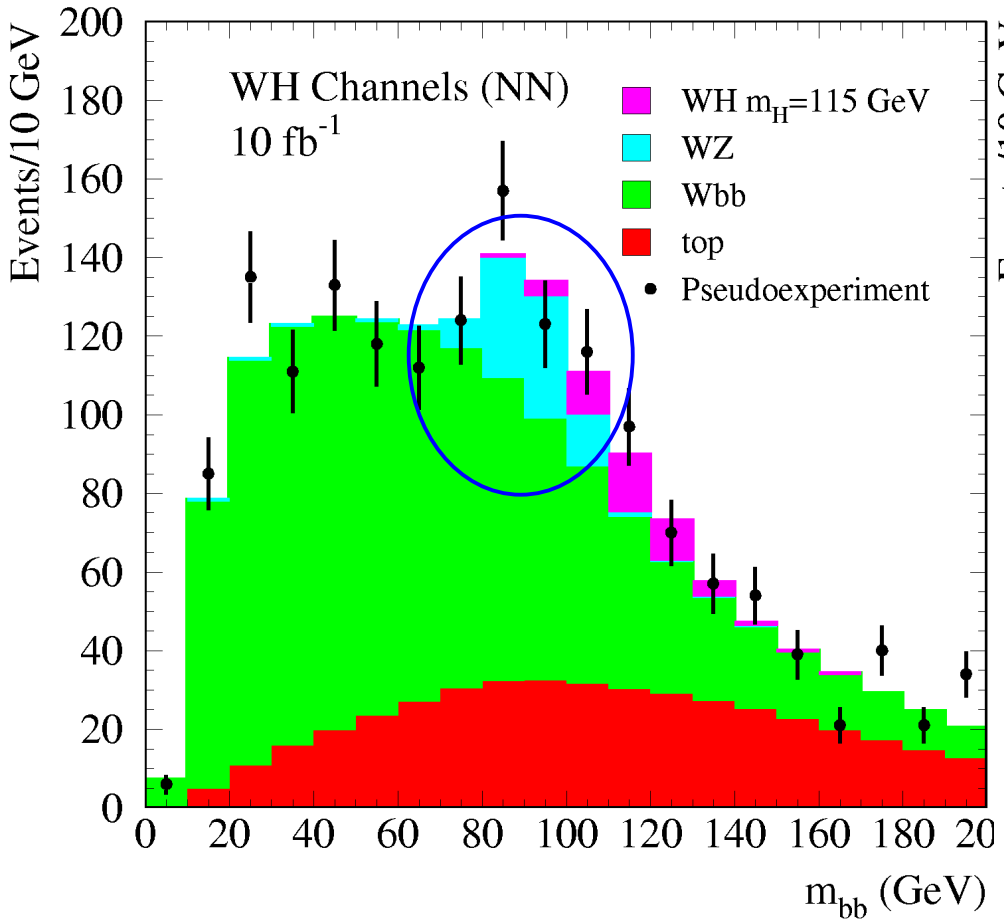
$\sigma(ZH;\ m_H = 115\ \text{GeV}) \approx 0.1$ pb

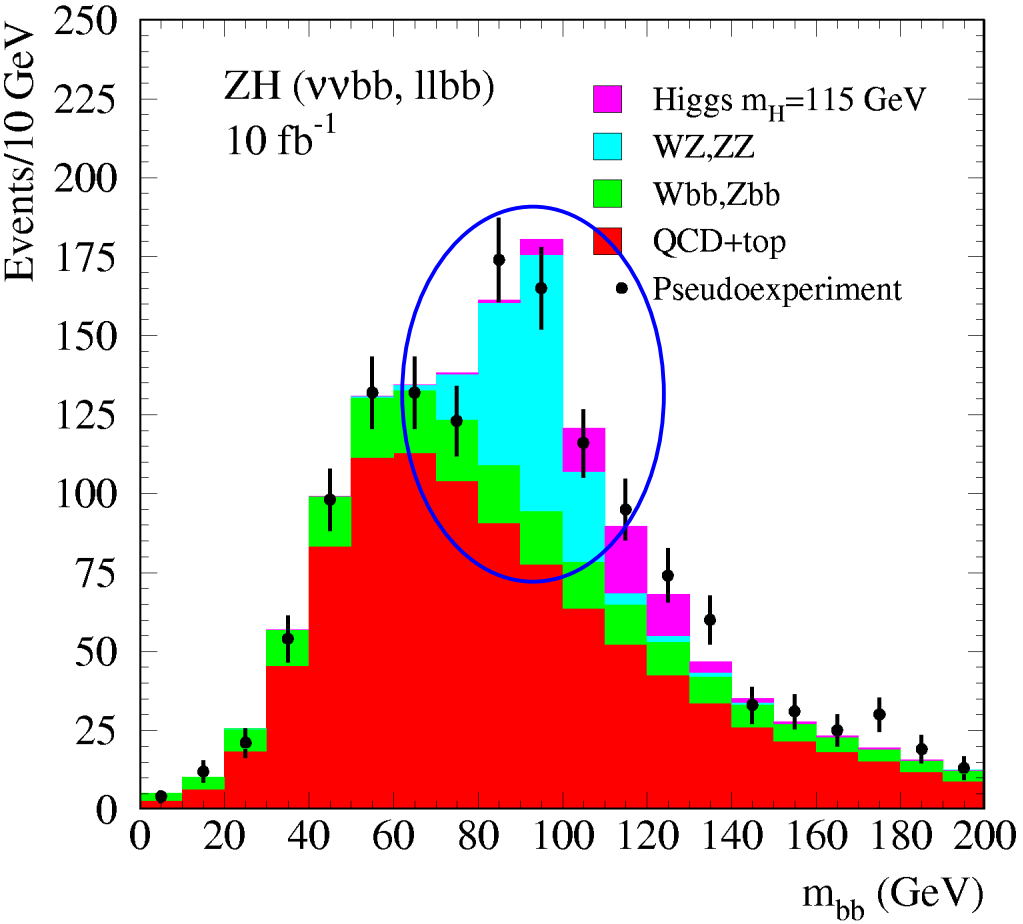
$\sigma(ZZ) \times BR(Z \to b\bar{b}) \approx 0.2$ pb

Major backgrounds
Calibration signals

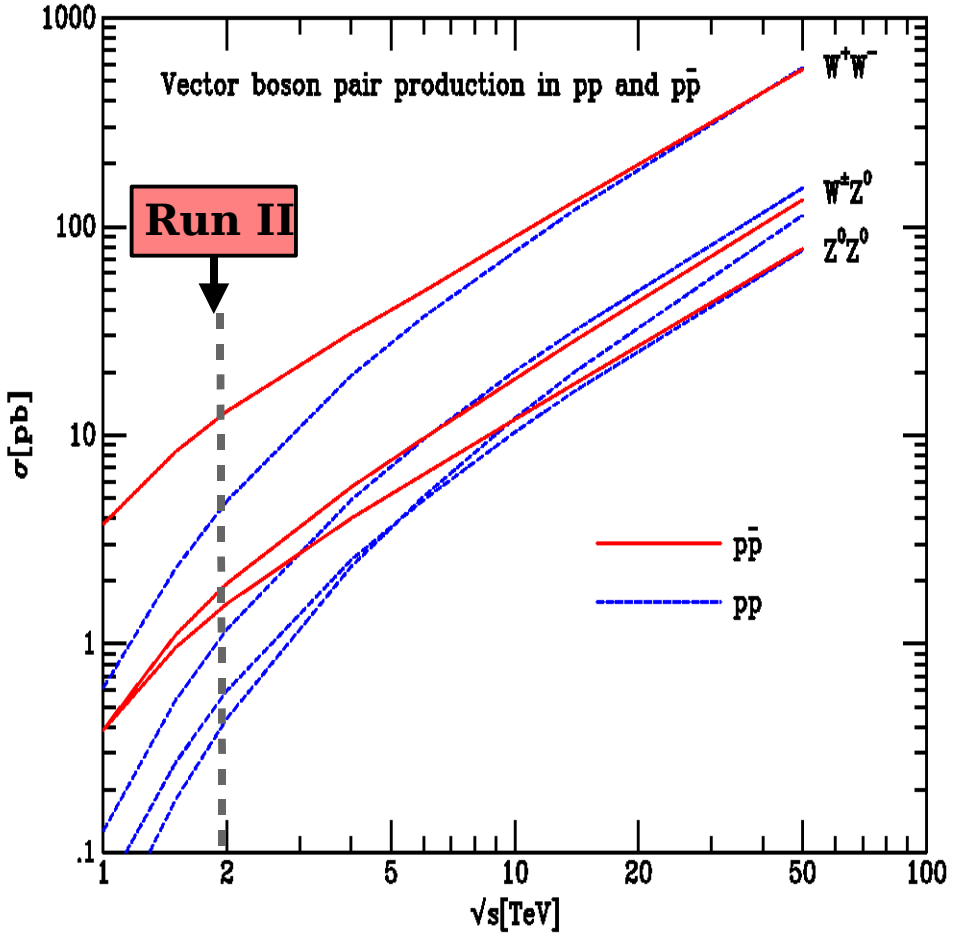
Relevance to Light Higgs Searches

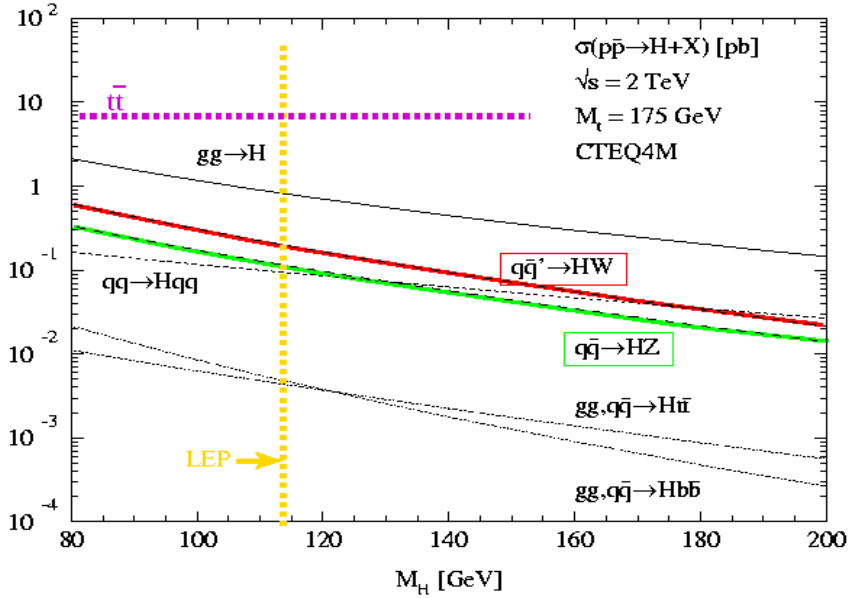
"Tevatron Higgs Sensitivity Study", 2003 :

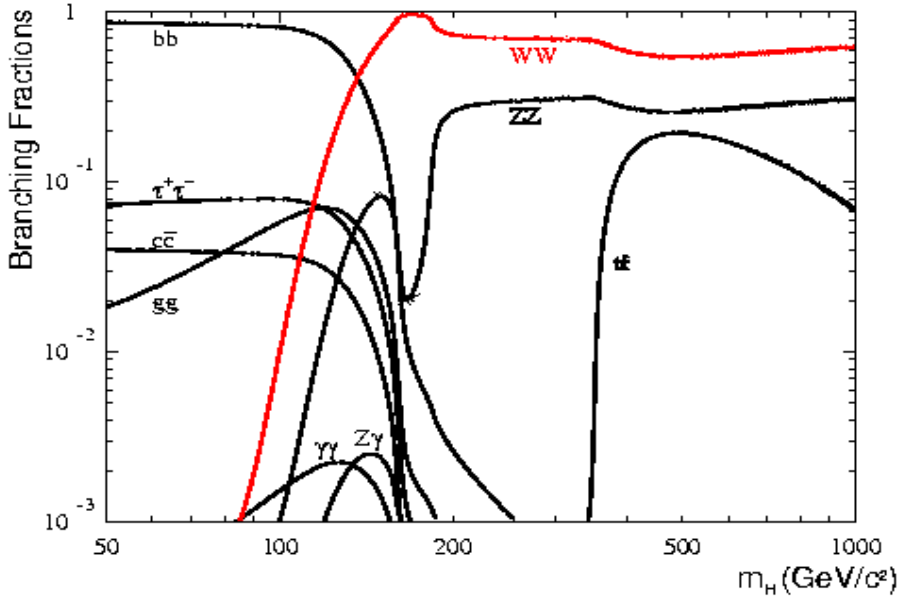




Diboson Production: Predictions







Photon Identification

EM cluster with $E_T > 7$ GeV

$|\eta^\gamma| < 1.1$ and $\Delta R(l,\gamma) > 0.7$

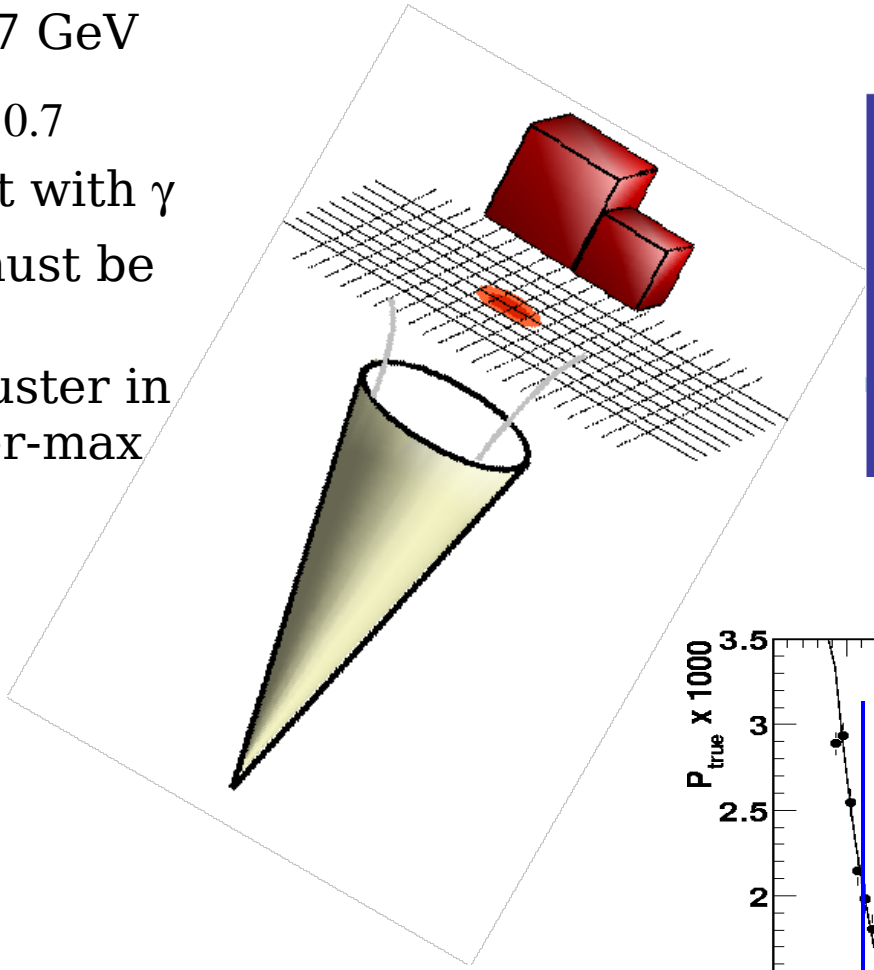
EM fraction consistent with γ

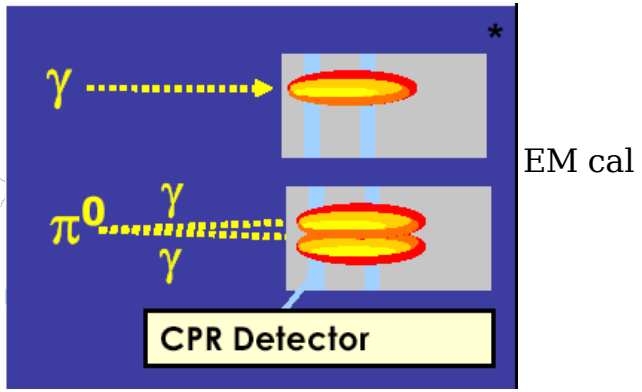
If ∃ matching track→must be soft

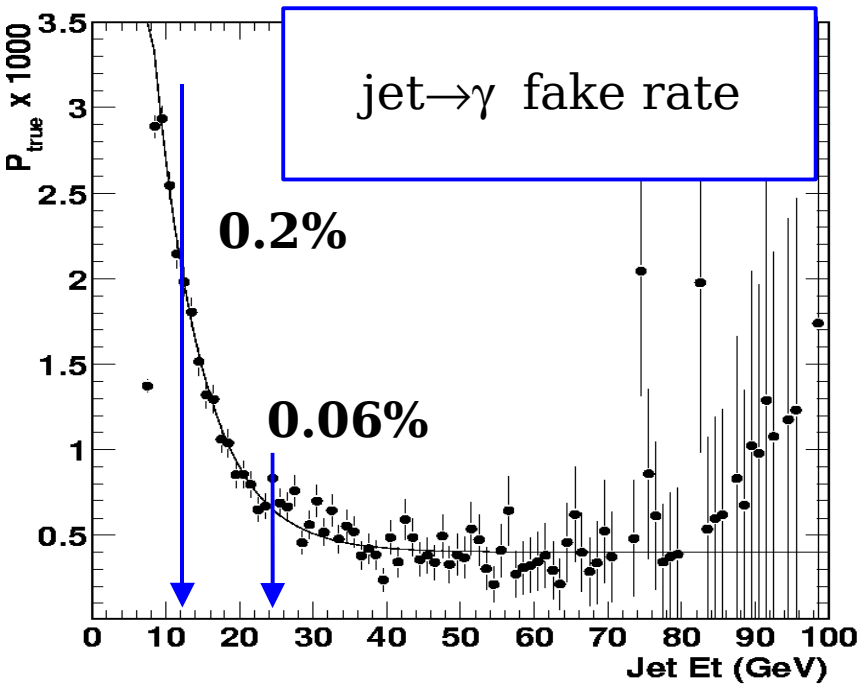
Well reconstructed cluster in both views of shower-max detector.

Calorimeter isolation.

Tracking isolation.



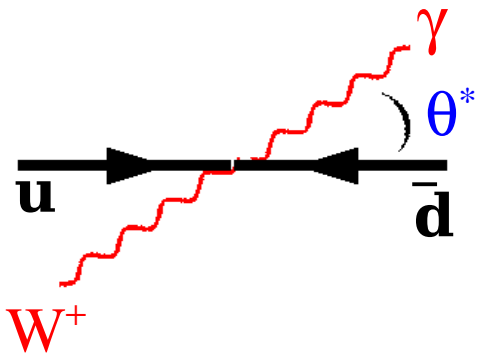


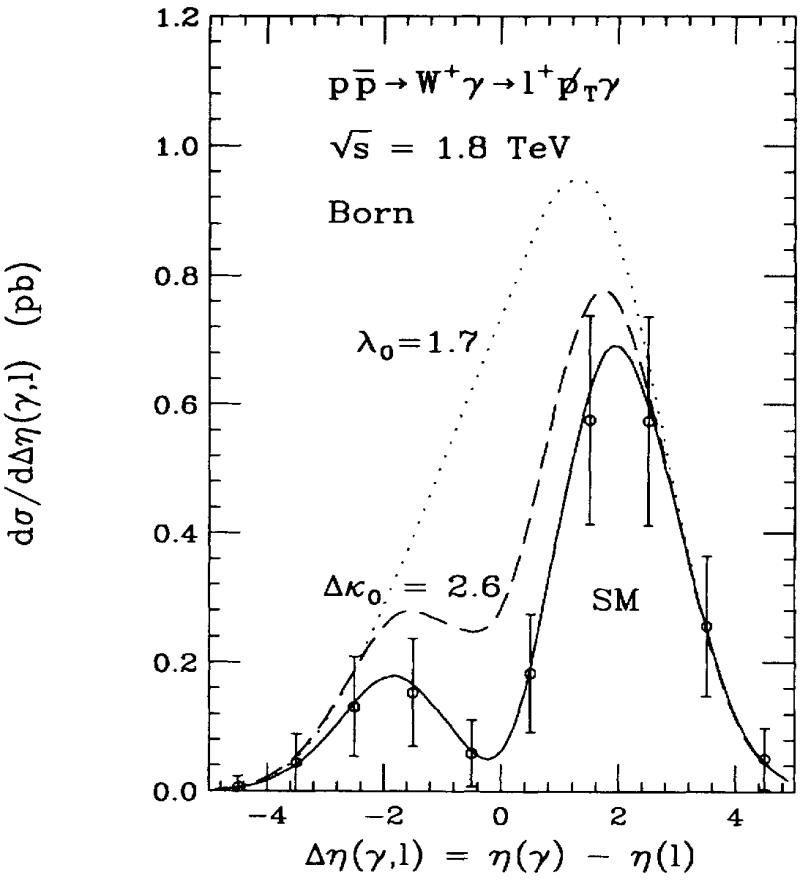


RAZ in Wγ

Radiation Amplitude Zero :

Mikaelain et al.,79; Baur, Errede, Landsberg 94.



$$\left| A^{t(ISR)} + A^{WW\gamma} \right| = 0$$
$$@\ \cos\theta^* = -1/3$$

observable as γ–lepton rapidity correlation