Di-boson production at the Tevatron

Outline

- Introduction
- WW cross section
- WZ cross section and WWZ couplings
- Wγ cross section and WWγ couplings
- Zγ cross section and tri-neutral couplings
- Conclusions

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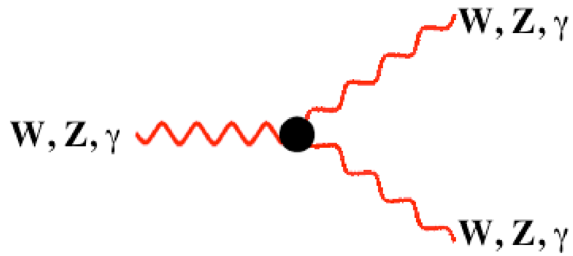
Moriond-EWK 2005, LaThuile, Italy, March 8, 2005

Motivations

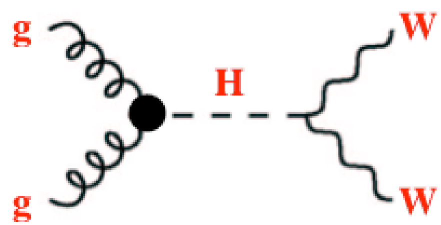
- Non-Abelian structure of SM => triple and quartic gauge boson couplings ∃ (ZZγ & Zγγ = 0)



- Diboson production

⇒ test of Triple Gauge Couplings (WWγ, WWZ, ZZγ, Zγγ)

- Tevatron is complementary to LEP:
  - Tevatron probes different coupling combinations than LEP
  - Tevatron explores higher $\hat{S}$



- New physics probe
- Background of numerous analyses (H->WW, SUSY, $t\bar{t}$)
- Knowledge of diboson cross section important for many LHC analyses
- At Run I, low statistics, low significance on diboson signal

WWγ & WWZ Anomalous couplings AC

- **All possible interactions terms (WWV; V = γ or Z) in L_{eff}:**

$$L_{WWV}/g_{WWV} = \boxed{g_V^1}(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + \boxed{\kappa_V} W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\boxed{\lambda_V}}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

- **L_{eff} characterized by 5 CP conserving parameters:**

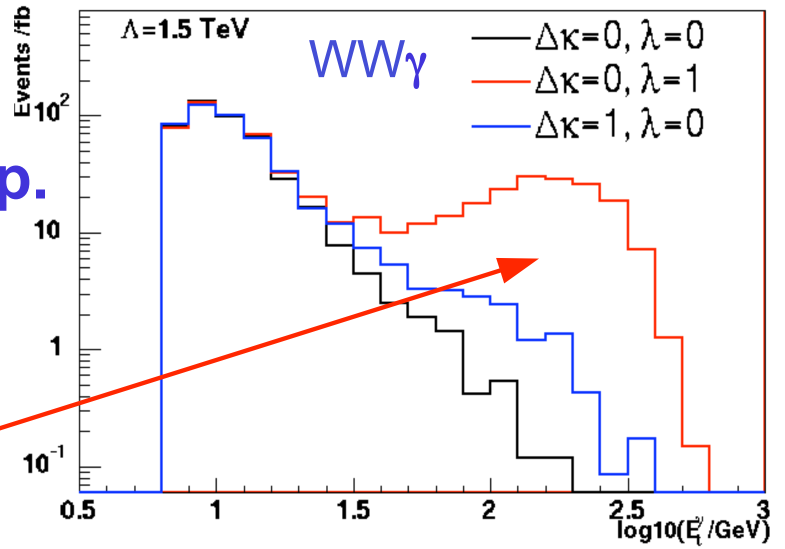
$\lambda_Z = \lambda_\gamma = 0$; $\Delta\kappa_Z = \Delta\kappa_\gamma = 0$ ($\Delta\kappa = \kappa - 1$) and $\Delta g^1_Z = 0$ ($\Delta g^1_Z = g^1_Z - 1$)

- **κ and λ related to magnetic dipole and electric quadrupole moments of W:**

$$\mu_W = e(1+\kappa+\lambda) / 2M_W$$

$$Q^e_W = -e(\kappa-\lambda) / M^2_W$$

- **form-factor scale Λ to avoid unitarity violation**
- **WW to probe WWγ and WWZ coup.**
- **Wγ to probe WWγ coupling**
- **WZ to probe WWZ coupling**
- **AC effect: X-section increases for high E_T boson**



Cut definitions

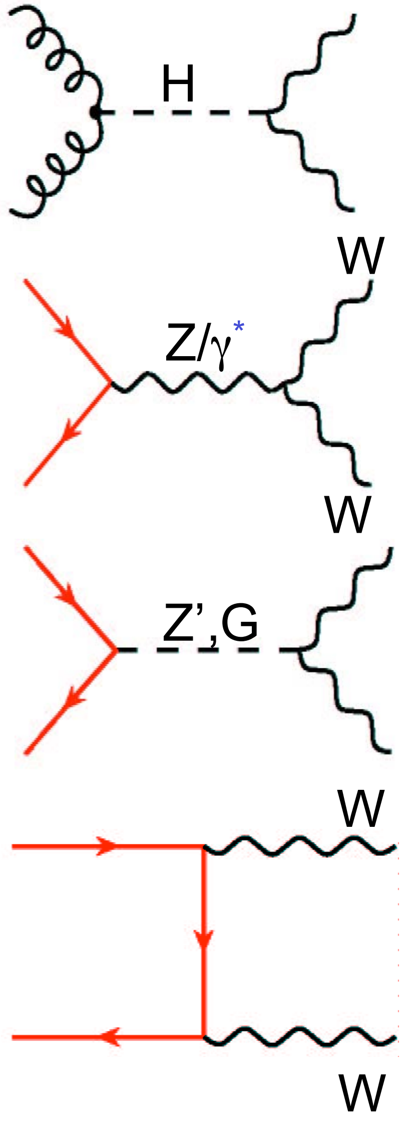
- CDF and D0 use similar cuts
- W/Z selections are based on selection of high-P_T leptons
  - Z->ll, W->lν
- High-P_T leptons
  - Electron or muon with P_T>20-25 GeV/c
  - Isolated = E_T in cone R=0.4 less than 0.1*E_T(lepton)
  - Central = $|\eta|$ <1 (1.1)

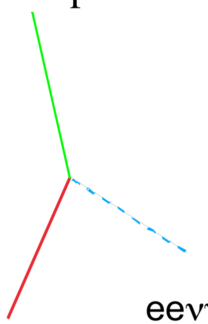
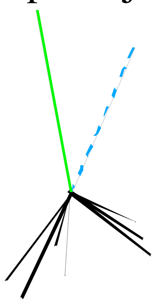
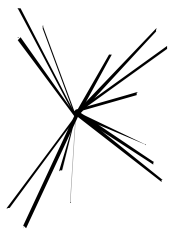
- Neutrinos result in mis-balance of transverse energy
  - Large missing E_T: $\not{E}_T$ > 20-25 GeV

WW production

- Important background for Higgs searches
- Self interaction of heavy bosons (WWγ/Z)
- Probe for new heavy bosons
- Large statistics at LEPII (10K evts/exp.)
- @ Run I, one result (CDF) w/. limited significance: 5 evts observed with 1.3±0.3 bkgrd.

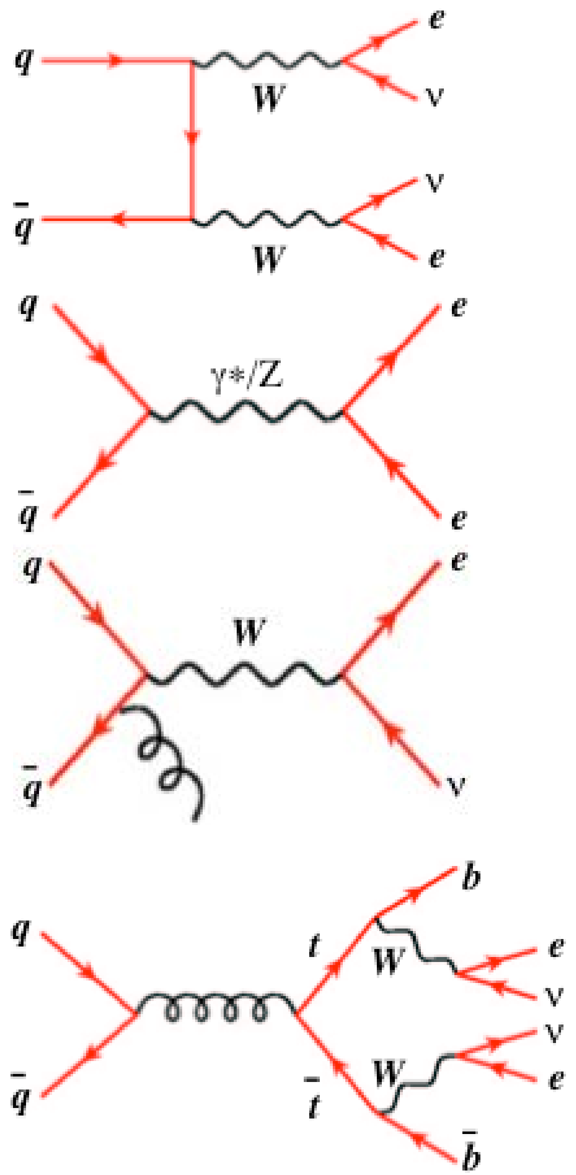
$\sigma\ (WW) = 10.2^{+6.3}_{-5.1}(stat) \pm 1.6\ (syst)\ pb$



Dileptons	Lepton+jets	All-jets
		
eμνν and eeνν, μμνν	en+jets, μν+jets	All-jets
Br = 2.5 and 1.2%	Br = 15%	Br = 47%
Pure and efficient Low branching frac.	Efficient Not very pure	Very efficient Never Mind

Event selection

- First goal: establish the signal
- Selection:
  - 2 isolated leptons
  - Large $\not{E}_T$ (2ν)
- Backrounds:
  - Drell-Yan with "fake" $\not{E}_T$
    - $\sigma(pp \to Z/\gamma^* \to ee) \sim 250$ pb
  - W+jets/γ where jet must fake a lepton
    - $\sigma(pp \to W(\to e\nu) + \geq 1\text{jet}) \sim 500$ pb
  - $t\bar{t}$ (contains additional jets)
    - $\sigma(pp \to t\bar{t} \to e\nu e\nu b\bar{b}) \sim 0.1$ pb
  - Heavy dibosons (WZ,ZZ) production



WW cross section

	D0 (224-252 pb^{-1})			CDF (184 pb^{-1})		
Process	ee	μμ	eμ	ee	μμ	eμ
WW signal	3.42±0.05	2.10±0.05	11.10±0.10	2.6±0.3	2.5±0.3	5.1±0.6
Total BKGD	2.30±0.21	1.95±0.41	3.81±0.17	$1.9^{+1.3}_{-0.3}$	$1.3^{+1.6}_{-0.4}$	1.9±0.4
Observed	6	4	15	6	6	5

Combined:

D0: $$\sigma(WW) = 13.8^{+4.3}_{-3.8}(stat.)^{+1.2}_{-0.9}(sys.) \pm 0.9(lum.)\ \text{pb}$$

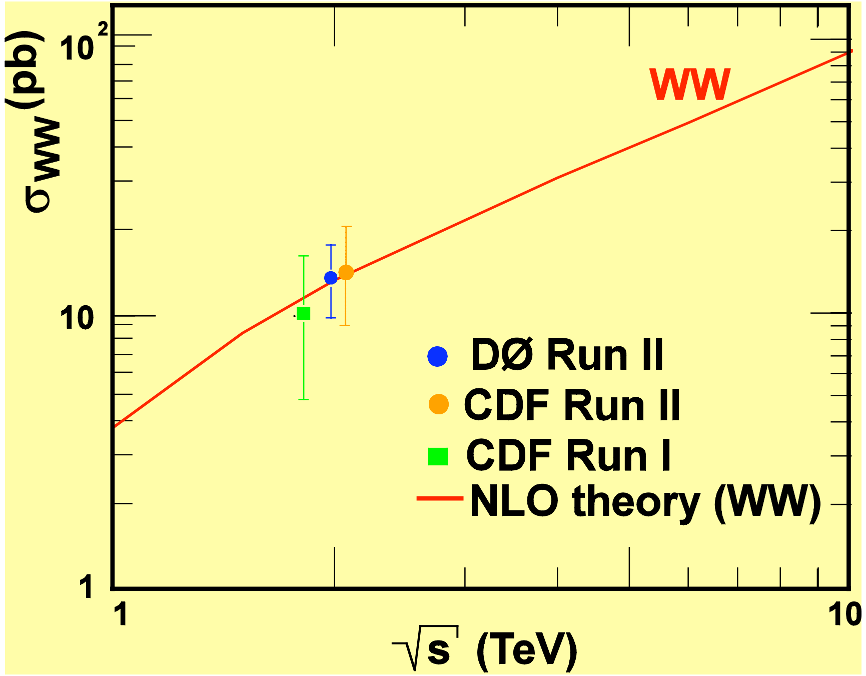
CDF: $$\sigma(WW) = 14.6^{+5.8}_{-5.1}(stat.)^{+1.8}_{-3.0}(sys.) \pm 0.9(lum.)\ \text{pb}$$

$\sigma(pp \to WW \to ll\nu\nu)^{THEORY}_{NLO}$ = 12.4±0.8 pb

P(background fluc.) = 2.3×10^{-7}
=> ~ 5.2 standard deviations

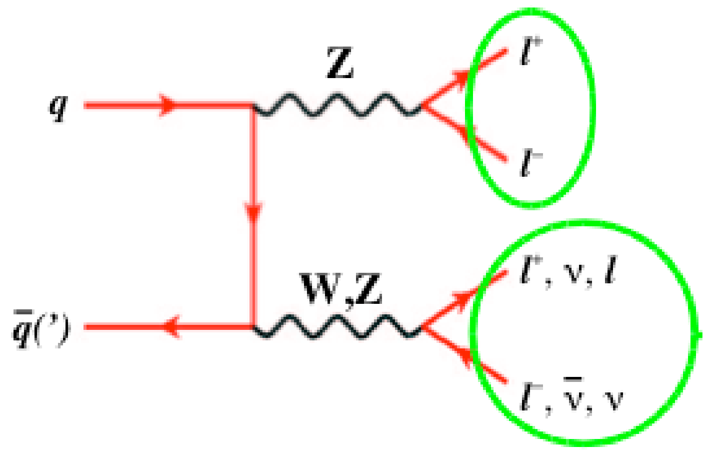
Systematics (CDF):

- Selection efficiency ~10%
  (signal modelling ~7%)
- Backgrounds ~40% (D-Y, W+jet)
- Luminosity : 6%



WZ

- Important step towards Higgs searches (significant bkgd)
- Sensitive to the WWZ coupling (and not WWγ as in WW)
- $W^{\pm}Z$ unavailable at e^+e^- colliders => unique meas. of WWZ
- Search for trilepton signature (no other SM process)
- $\sigma_{NLO}(WZ)$ ~ 4.0 pb at 1.96 TeV
- Z selection:
  - 2 high P_T leptons
  - $M_{inv}(ll)$ consistent w/ m_Z
- W selection:
  - Isolated lepton + $\not{E}_T$
- Main background:
  - Z/γ^*+ jet



CDF WZ and ZZ x-sections

Process	4 leptons	3 leptons	2 leptons	Combined
ZZ	0.06±0.01	0.13±0.01	0.69±0.11	0.88±0.13
ZW	-	0.78±0.06	0.65±0.10	1.43±0.16
Total signal	0.06±0.01	0.91±0.07	1.34±0.21	2.31±0.29
WW	-	-	0.40±0.07	0.40±0.07
Fake	0.01±0.02	0.07±0.06	0.21±0.12	0.29±0.16
Drell-Yan	-	-	0.31±0.17	0.31±0.17
$t\bar{t}$	-	-	0.02±0.01	0.02±0.01
Total Bkgd	0.01±0.02	0.07±0.06	0.94±0.22	1.02±0.24
Signal+Bkgd	0.07±.02	0.98±0.09	2.28±0.35	3.33±0.42
#Observed	0	0	3	3

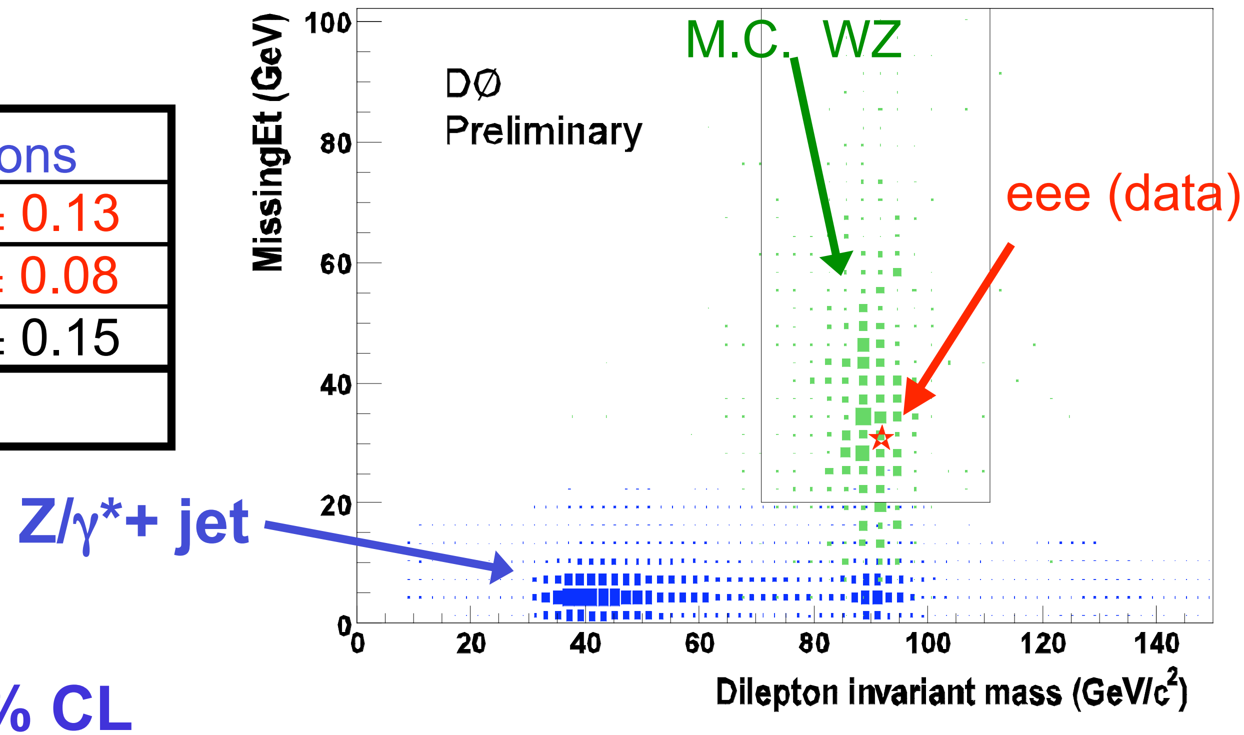
- **Upper limit at 95%CL:**

σ(pp_ZZ/ZW+X) <15.2 pb @95% C.L.

$\sigma(\text{pp\_ZZ/ZW+X})^{\text{THEORY}}_{\text{NLO}} = 5.0 \pm 0.4$ pb

D0 WZ cross section

D0(285-320pb^{-1})	3 leptons
WZ signal	2.04 ± 0.13
Bckgd	0.71 ± 0.08
Expec. Total	2.75 ± 0.15
Observed	3



- **Upper limit at 95% CL**
  - **σ(pp_ZW+X)<13.3 pb @95% C.L**
- **WZ cross section estimate**
  - **σ(pp_ZW+X) = $4.5^{+3.5}_{-2.6}$pb**
- **Prob (0.71 bkgd->3 candidates) = 3.5%**

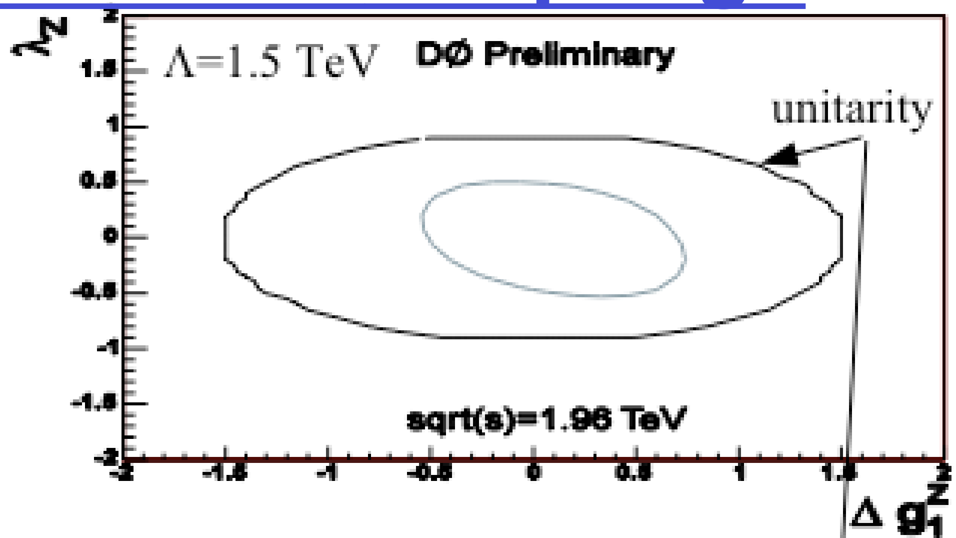
WWZ anomalous trilinear couplings

- **Generate a grid of WZ M.C.**

(Hagiwara, Woodside, + Zeppenfeld LO generator + Fast Detector Simulation)

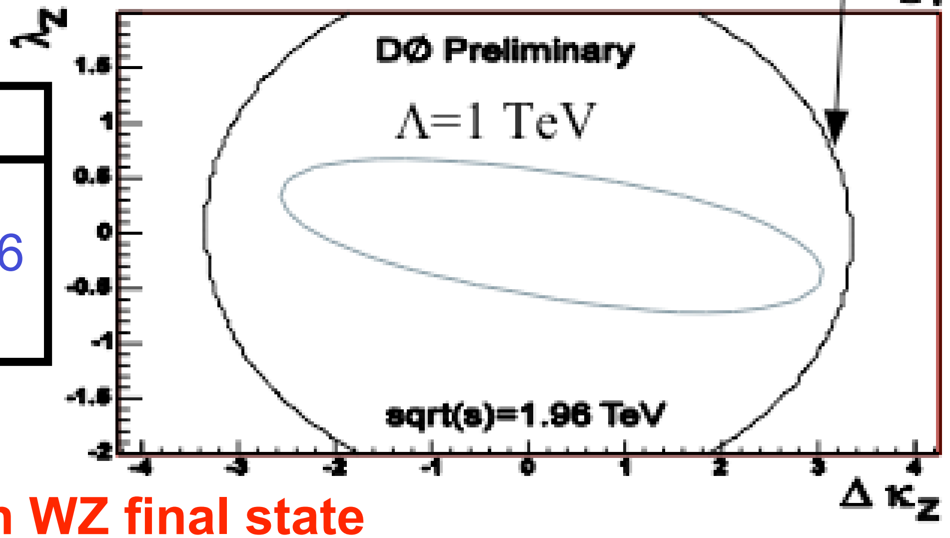
- **Form Ln(Likelihood)**
- **Intersect with plane at**

Max-3.0=> 2D limit at 95%CL



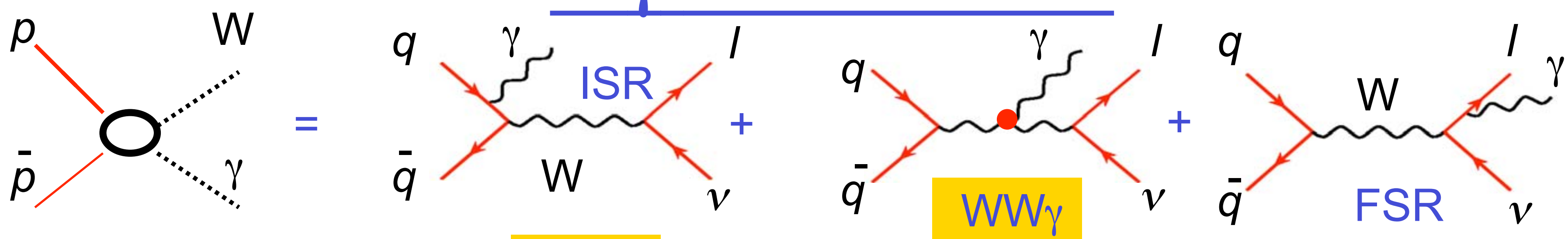
1D limits at 95% CL (D0)

Λ = 1.0 TeV	Λ = 1.5 TeV
$-0.53 < \lambda_Z < 0.56$	$-048 < \lambda_Z < 0.48$
$-0.57 < \Delta g^1{}_Z < 0.76$	$-0.49 < \Delta g^1{}_Z < 0.66$
$-2.0 < \Delta\kappa_Z < 2.4$	—



- **Best limits on WWZ couplings in WZ final state**
- **First 2D limits in κ_Z vs λ_Z using WZ**
- **Best limits on $\Delta g^Z{}_1$, $\Delta\kappa_z$ and λ_Z from direct, model independent measur.**
- **D0 Run II 1D limits are x3 better than Run I**

Wγ Production



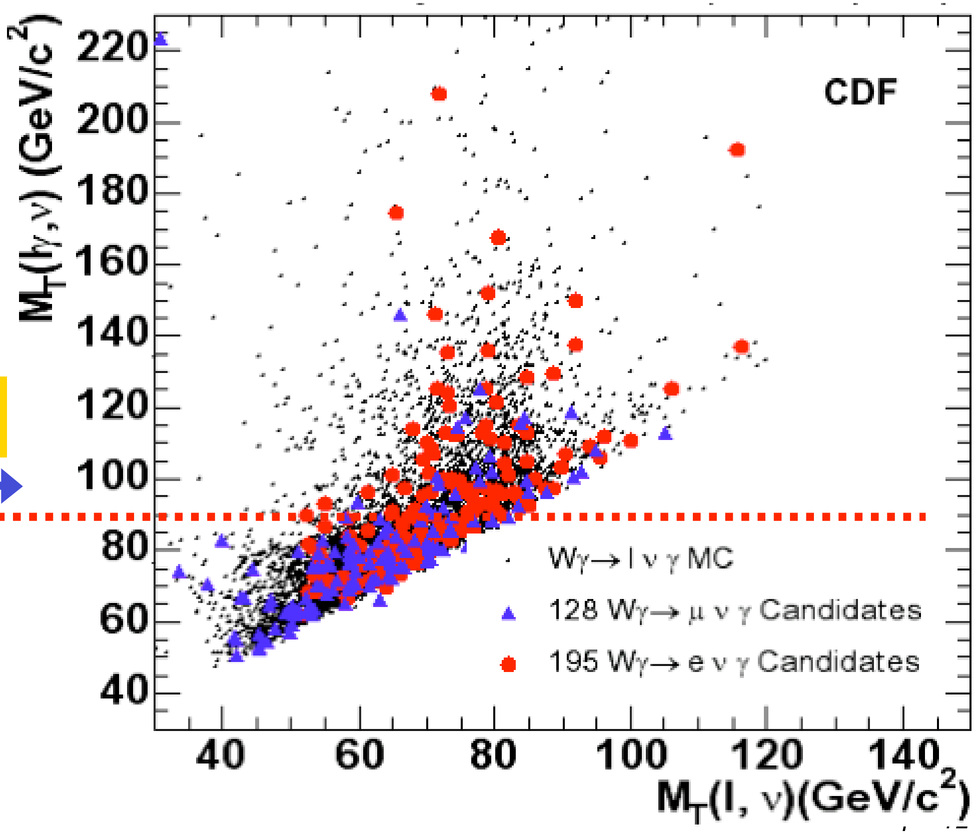
- **Sensitive only to WWγ coupling**
- **Bkgd of Gauge Mediated Supersymmetry Breaking models**
- **W Selection**
  - **Isolated high-P_T lepton**
  - **Large $\not{E}_T$**
- **γ ID is crucial**

  $|\eta| < 1$, $\Delta R(l,\gamma) > 0.7$

Effect of anomalous couplings more pronounced at high $M_T(W\gamma)$

ISR + WWγ

FSR



$W\gamma$ cross section

Decay Channel	D0 $e\nu\gamma$	D0 $\mu\nu\gamma$	CDF $e\nu\gamma$	CDF $\mu\nu\gamma$
Lum'y (pb^{-1})	162 (6.5%)	134 (6.5%)	202-168 (6%)	192-175(6%)
$W\gamma$	51.2 ± 11.5	89.7 ±13.7	126.8 ± 5.8	95.2 ± 4.9
Total Bkgrd	60.8 ± 4.5	71.3 ± 5.2	67.3 ± 18.1	47.3 ± 7.6
Sig+Bkgd	112 ± 12.3	161 ± 14.6	194.1 ± 19.1	142.5 ± 9.5
# Observed	112	161	195	128
A*ε	2.3%	4.4%	3.3%	2.4%
$\sigma(W\gamma)$*Br	13.9±2.9±1.6	15.2±2.0±1.1	19.4±2.1±2.9	16.3±2.3±1.8

Combined*:

D0:

$$\sigma(p\bar{p} \rightarrow W^{\pm}\gamma) = 14.8 \pm 1.6(stat.) \pm 1.0(sys.) \pm 1.0(lum.)\ \mathrm{pb}$$

SM expect: $\sigma(W\gamma)$ = 16.0 ± 0.4 pb

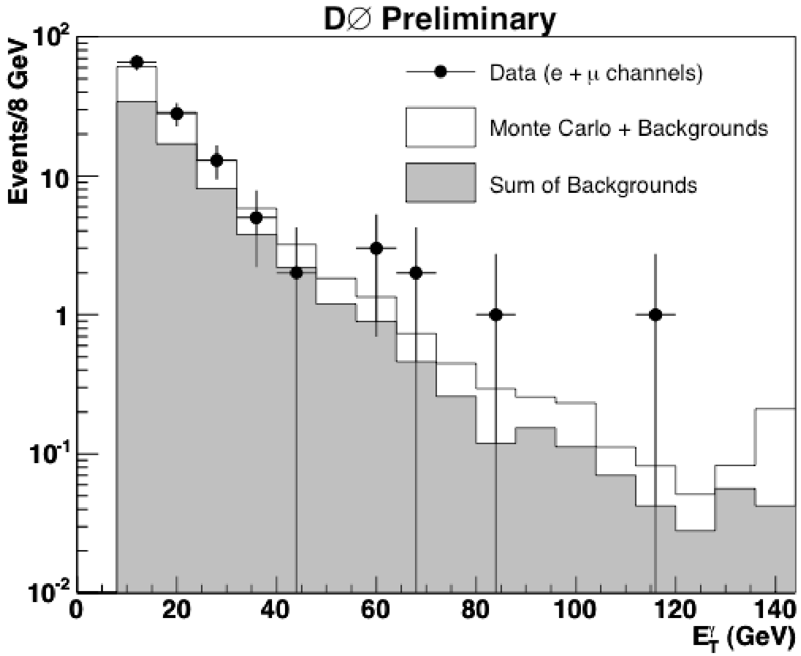
CDF:

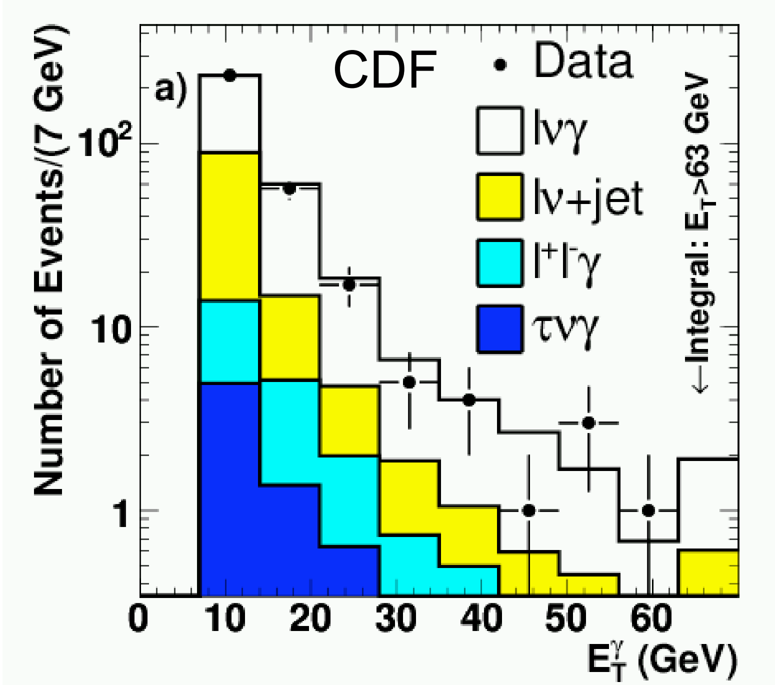
$$\sigma(p\bar{p} \rightarrow W^{\pm}\gamma) = 18.1 \pm 3.1\ \mathrm{pb}$$

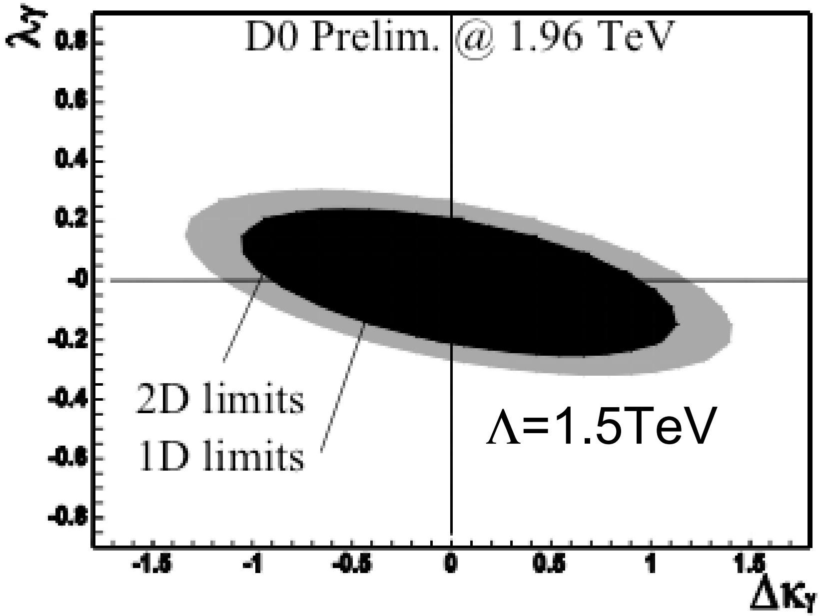
SM expect: $\sigma(W\gamma)$ = 19.3 ± 1.4 pb

*Both experiments quote x-section integral within acceptance

WWγ anomalous coupling





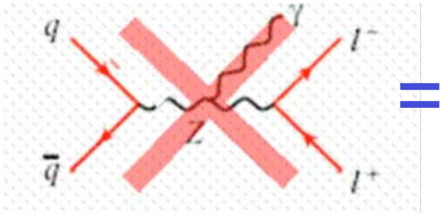


1D limits at 95% CL (D0):

	Tev Run I	Tev Run II	LEP comb.
$\Delta\kappa$	-0.93, 0.94	-0.93, 0.97	-0.105, 0.069
λ	-0.31, 0.29	-0.22, 0.22	-0.059, 0.026

Run I limit on λ already improved!
The tightest at a hadron collider

Zγ production

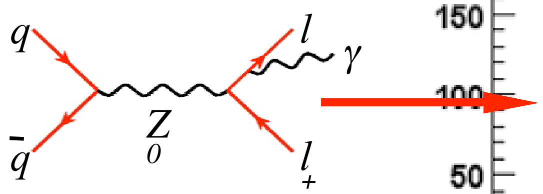


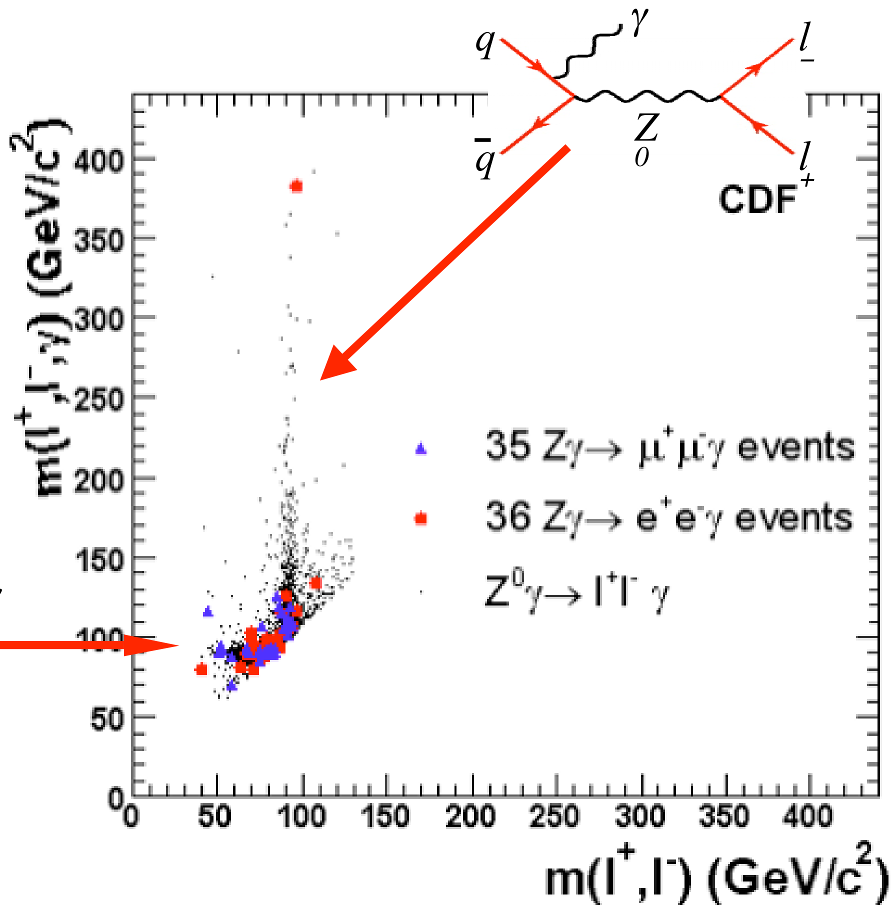
=0 ?

L_{eff} with 8 couplings parameters (h_1^V, h_2^V, h_3^V, h_4^V ; V = Z,γ).
In SM all these couplings =0

- **Zγ selection:**
  - **2 high-P_T isolated leptons**
  - **$40 < M_{inv}(l,l) < 110$ GeV**
  - **1 photon $|\eta<1.1|$ with $E_T>7$ GeV (8 GeV @ D0),**

- **Main Background = Z+jet where jet mimic a photon (see Wγ)**





Zγ cross section

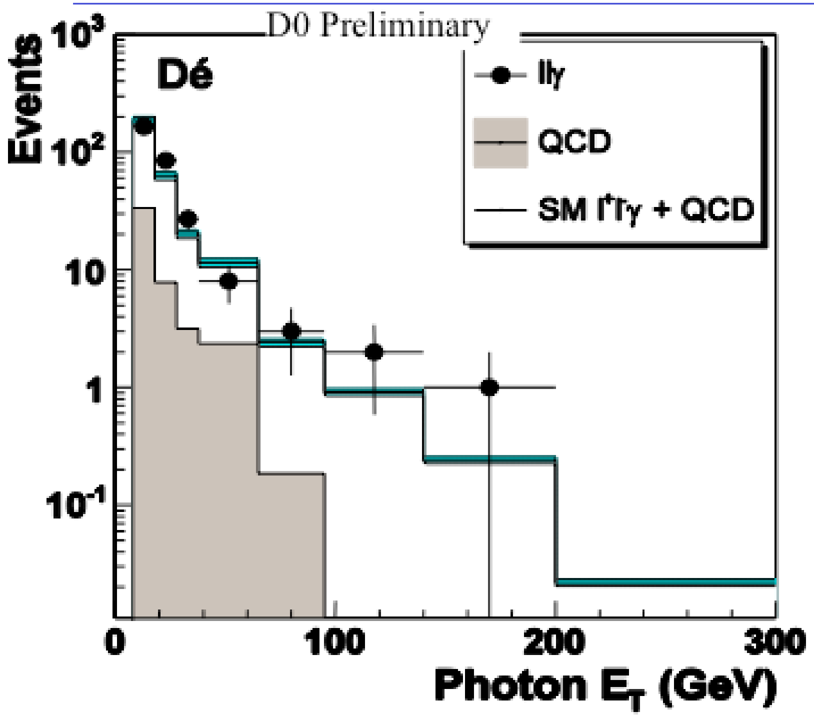
- **Summary:**

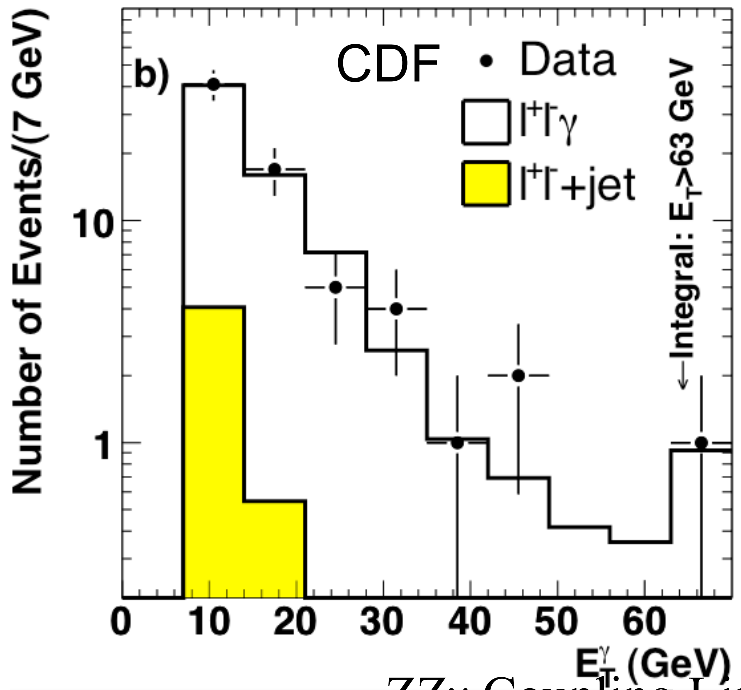
Decay Channel	D0 eeγ	D0 μμγ	CDF eeγ	CDF μμγ
Lum'y (pb^{-1})	324 (6.5%)	286 (6.5%)	202-168 (6%)	192-175 (6%)
SM Zγ	109 ± 7	128 ± 8	31.3 ± 1.6	33.6 ± 1.5
Total Bkgrd	23.6 ± 2.3	22.4 ± 3.0	2.8 ± 0.9	2.1 ± 0.7
Sig+Bkgrd	132.6 ± 7	150.4 ± 8	34.1 ± 1.8	35.7 ± 1.7
# Observed	138	152	36	35
A∗ε	11.3%	11.7%	3.4%	3.7%
σ∗Br(pb)	–	–	4.8±0.8±0.3	4.4±0.8±0.2

- **Combined:**
  - σ(Zγ)*Br(Z ->ll) = 4.6 ± 0.6 pb (CDF)
  - σ(Zγ)*Br(Z ->ll) = 4.2 ± 0.4(stat+syst) ± 0.3 (lumi) pb (D0)
  - SM expectation: 4.5 ± 0.3 (pb)

*Both experiments quote x-section integral within acceptance

Kin. distributions & tri-neutral coupling

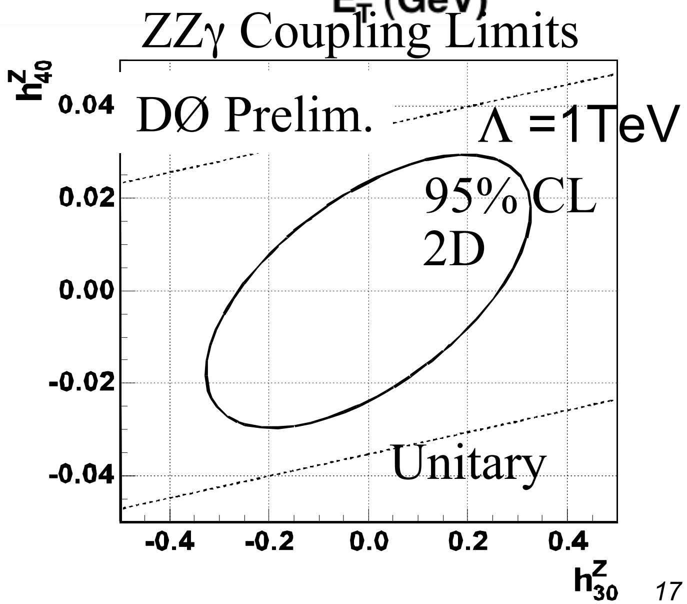




1D limits at 95% CL

LEP	Tevatron (D0)
$-0.049 < h^{\gamma}_{30} < 0.008$	$-0.23 < h^{\gamma}_{30} < 0.23$
$-0.002 < h^{\gamma}_{40} < 0.034$	$-0.019 < h^{\gamma}_{40} < 0.019$
$-0.20 < h^{Z}_{30} < 0.07$	$-0.23 < h^{Z}_{30} < 0.23$
$-0.05 < h^{Z}_{40} < 0.12$	$-0.020 < h^{Z}_{40} < 0.020$

Already better than LEP!



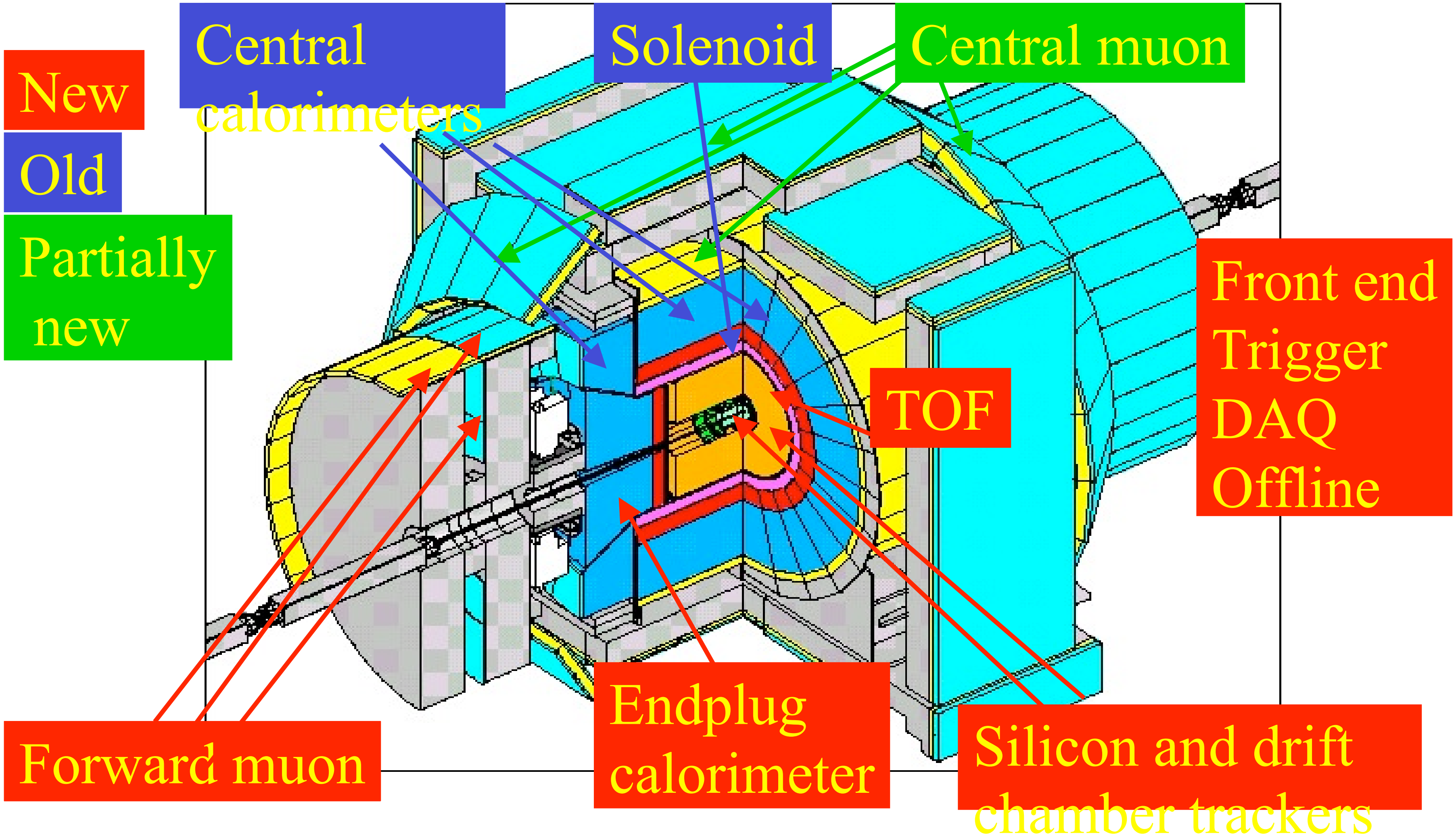
Conclusions

- Most of Run I measurements re-established and/or already improved + new Run II results:
  - Significant number of diboson candidate events
  - Very good agreement with SM
  - CDF and D0 have measured $\sigma(WW)$ at 1.96 TeV using the dilepton decay channel
  - CDF and D0 have 95% CL on $\sigma(WZ/WZ+ZZ)$ and D0 has first evidence of WZ production
  - D0 has tightest limit on WWZ anomalous coupling using WZ events.
  - Both CDF and D0 study the $W\gamma$ and $Z\gamma$ production
    - tightest limit on $WW\gamma$ anomalous coupling at hadron collider

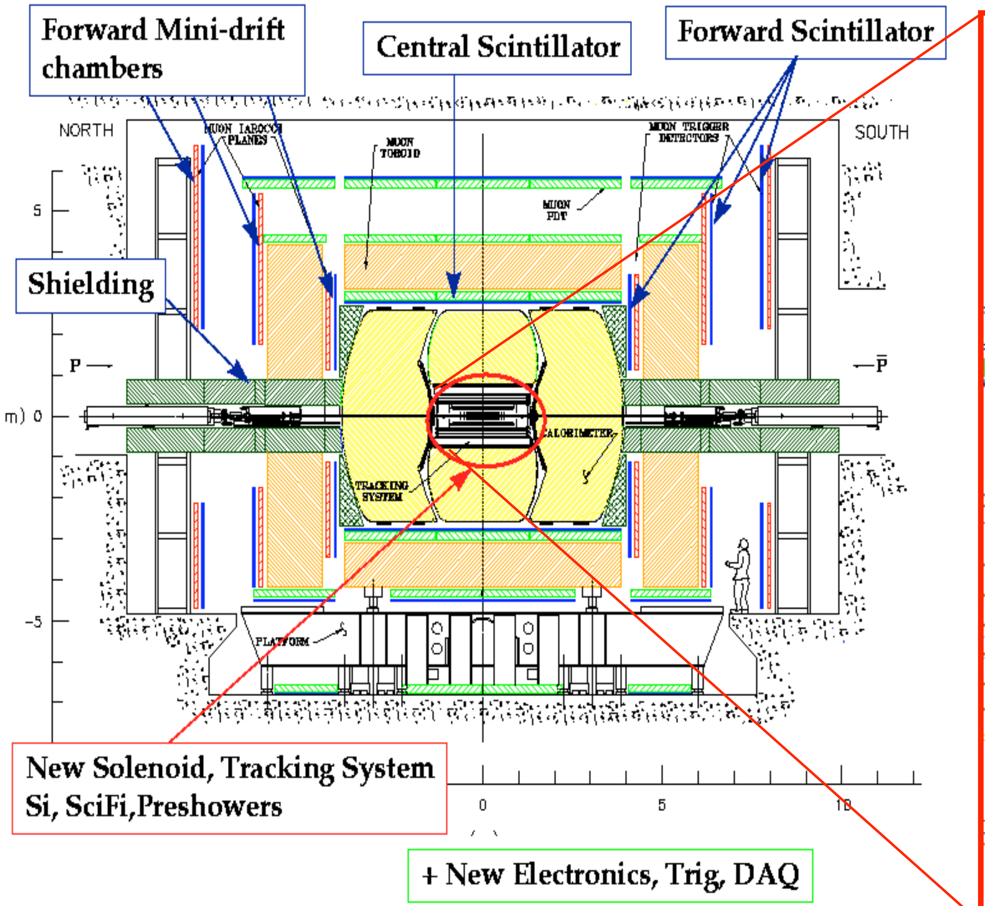
- More to come:
  - CDF and D0 start only exploring the potential of Tevatron Data
  - Radiation amplitude zero ($WW\gamma$ AC)
  - Use jet channel $WW \to l\nu jj$
  - Quartic couplings
  - …

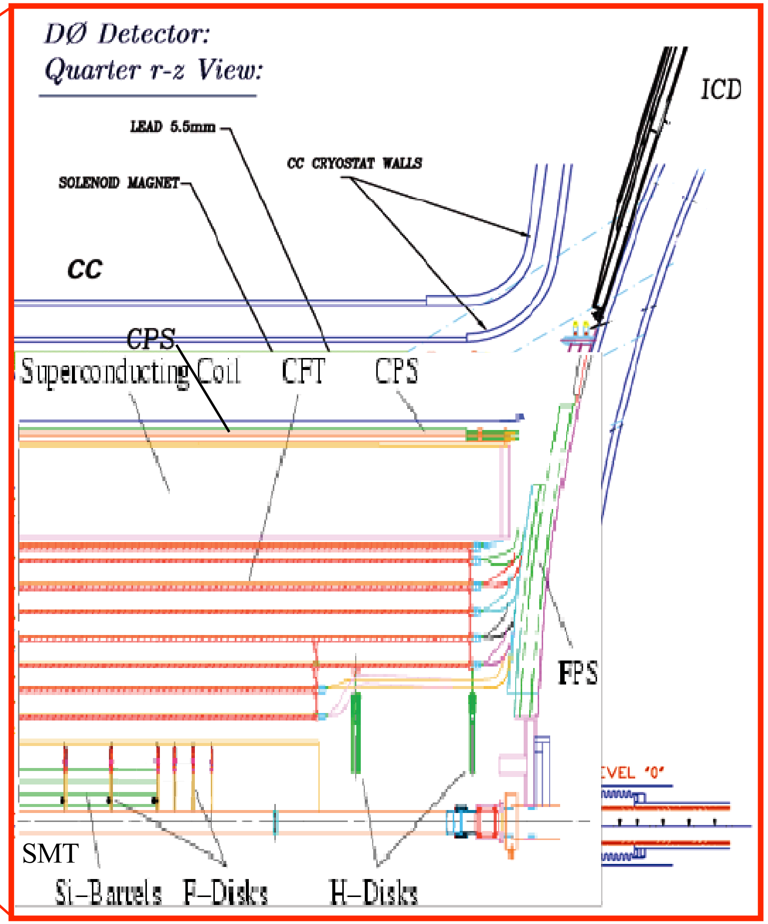
Backup slides

CDF detector



D0 detector


Forward Mini-drift chambers
Central Scintillator
Forward Scintillator
Shielding
NORTH
SOUTH
MUON TOROID
CALORIMETER
TRACKING SYSTEM
PLATFORM
New Solenoid, Tracking System
Si, SciFi,Preshowers
+ New Electronics, Trig, DAQ


DØ Detector:
Quarter r-z View:
ICD
LEAD 5.5mm
CC CRYOSTAT WALLS
SOLENOID MAGNET
CC
CPS
Superconducting Coil
CFT
CPS
FPS
SMT
Si–Barrels
F–Disks
H–Disks

WW –>eeνν Event Selection

- **ee channel criteria**
  - Minimal Transverse Mass > 60 GeV/c^2.
  - .NOT. 76<M(ee)<106 GeV/c^2.
  - "Scaled MET" > 15 rootGeV

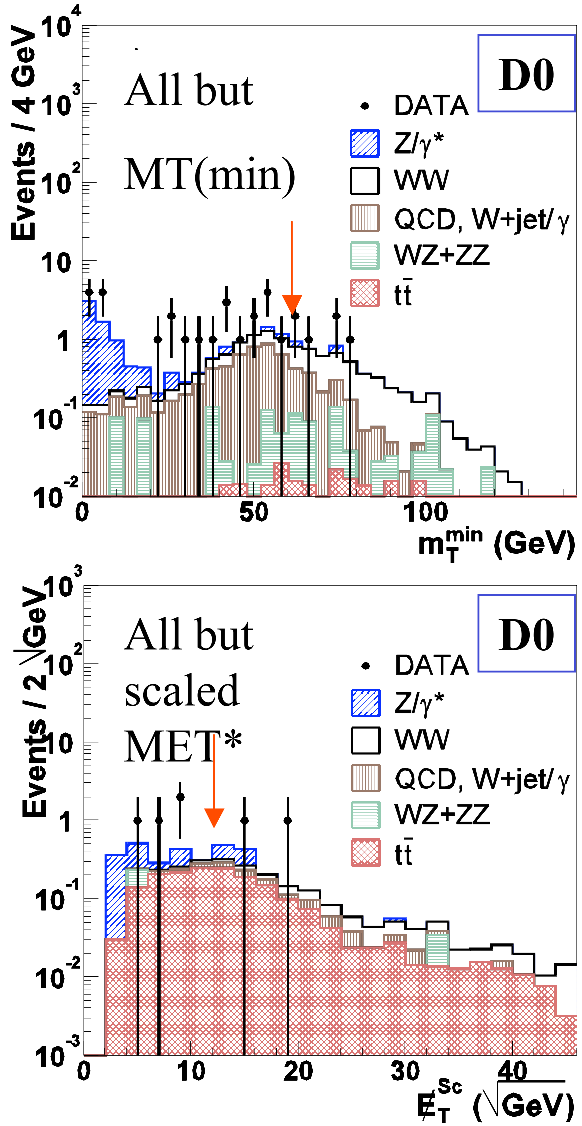
$$\not{E}_T^{Sc} \equiv \frac{\not{E}_T}{\sqrt{\sum_{jets} (\Delta E^{jet} \cdot \sin\theta^{jet} \cdot \cos\Delta\varphi(jet, \not{E}_T))^2}}$$

  - H_T(jets w/ E_T>20 &|η|<2.5) <50 GeV.

Remove Z/γ*

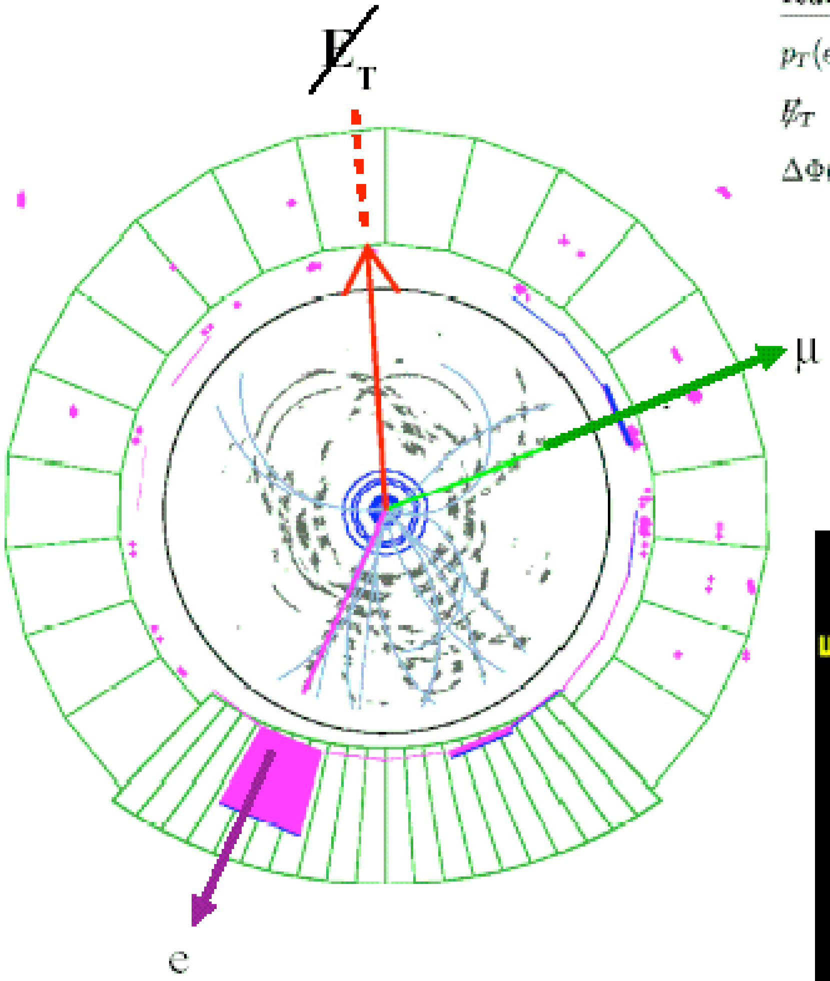
Remove Top pairs

- Background is 2.30+–0.21 events and is 60% W+jets, 40% mixed heavy.
- Eff'y is 8.76+–0.13%.
- Expected signal is 3.42+–0.05 events.
- 6 Candidates Observed.



*Events with jet(s).

WW->eν+μν$_\mu$



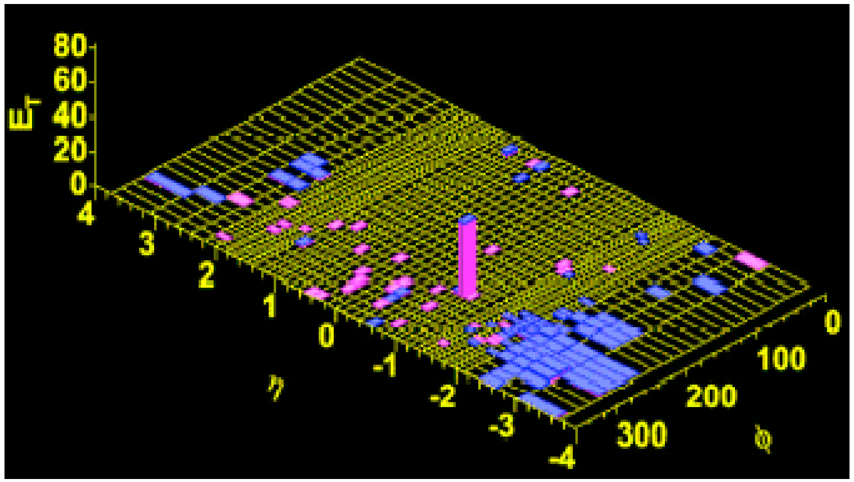
Run 155364 Event 3494901 : $WW \to e^+\nu_e\mu^-\bar{\nu}_\mu$ Candidate

$p_T(e) = 42.0$ GeV/c; $p_T(\mu) = 20.0$ GeV/c; $M_{e\mu} = 81.5$ GeV

$\not{E}_T = 64.8$ GeV; $\Phi(\not{E}_T) = 1.6$

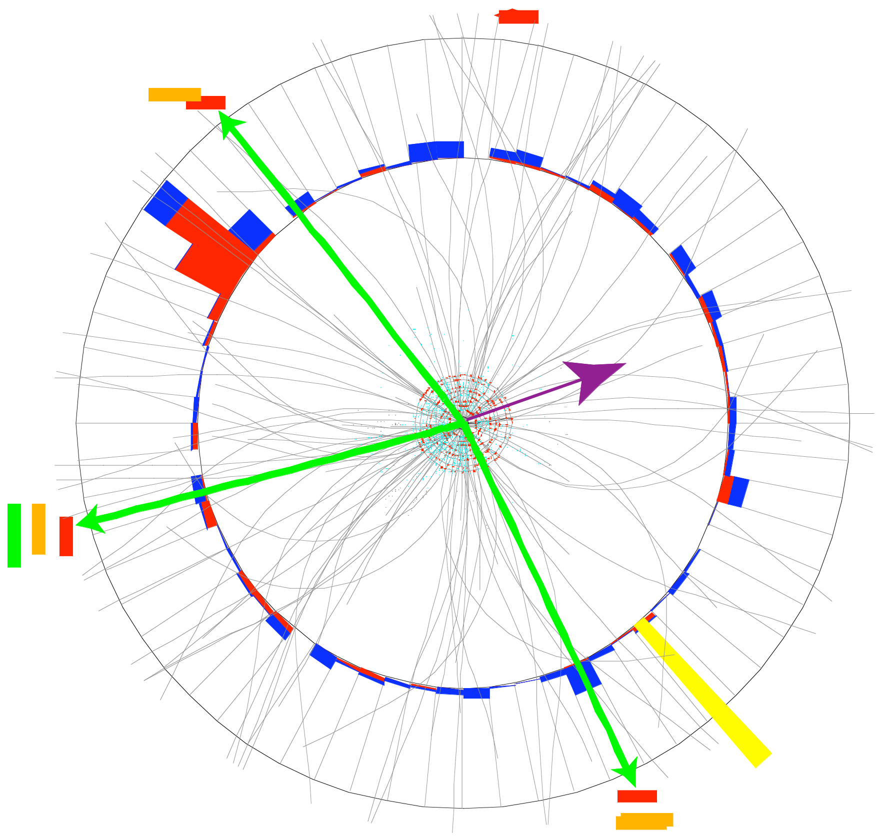
$\Delta\Phi(\not{E}_T, \text{lepton}) = 1.3$; $\Delta\Phi(e, \mu) = 2.4$; Opening-Angle(e, μ)=2.6

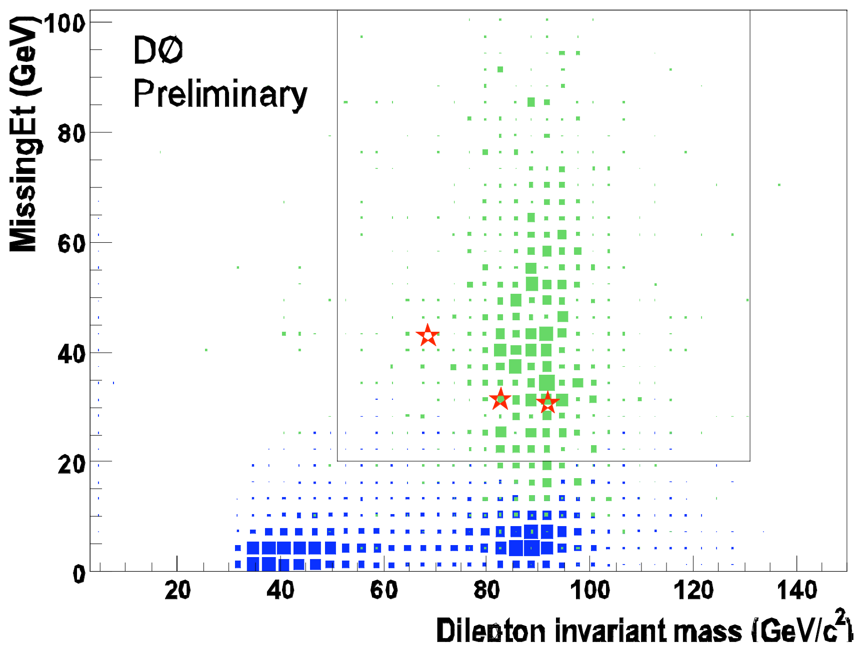
- eμ channel has little Standard Model background
- Signal/Background = 4



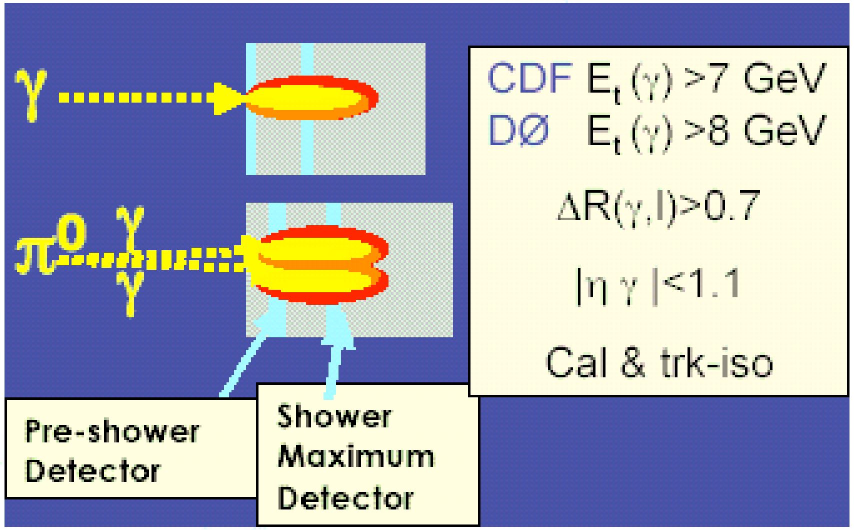
WZ

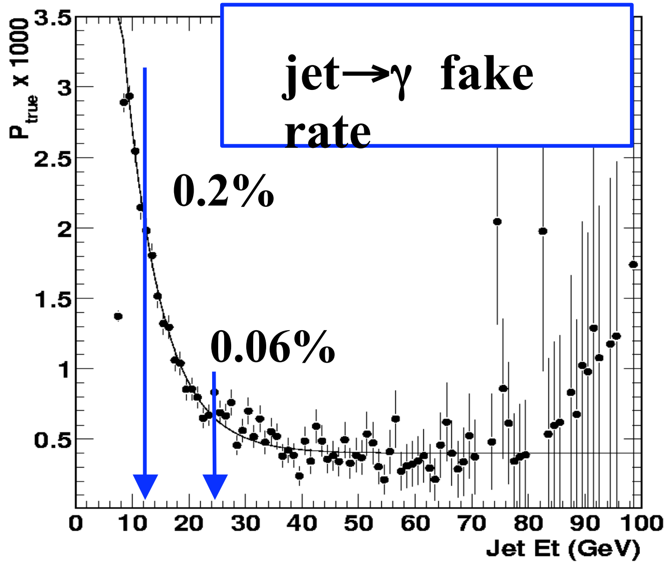
- The 3 events



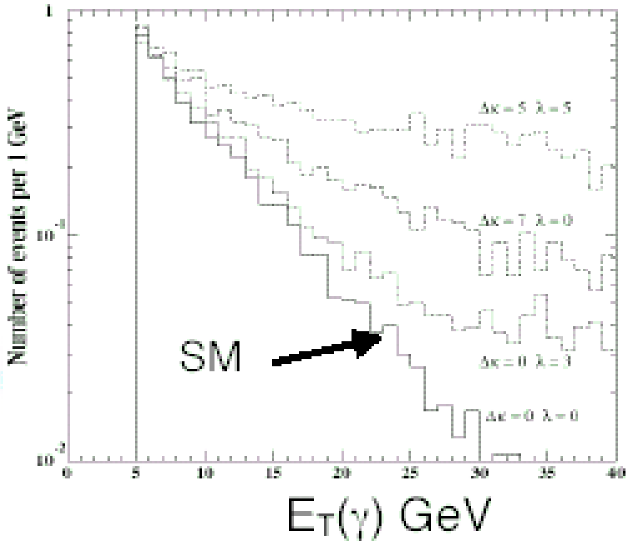


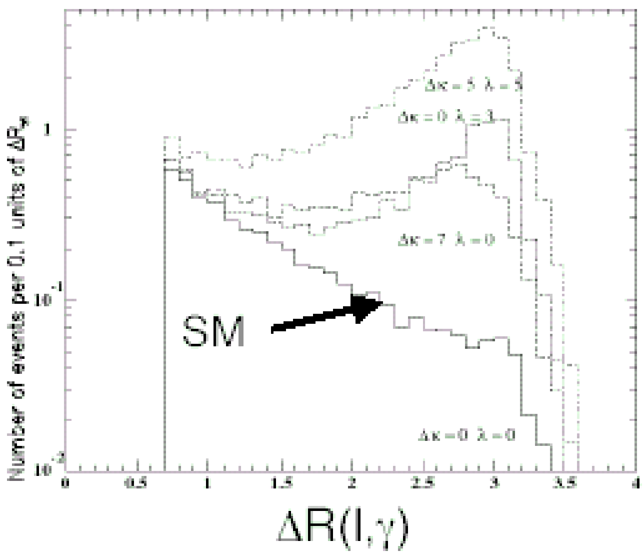
Wγ production





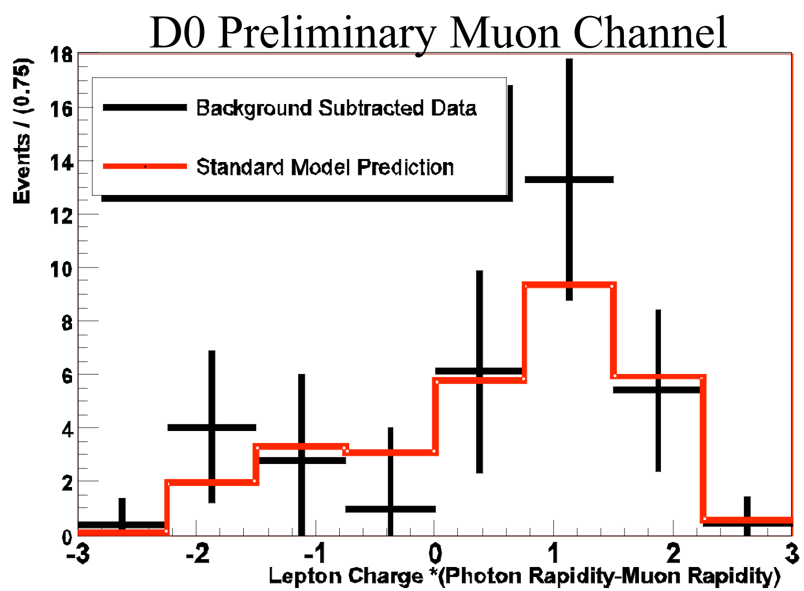
cluster transverse mass $M_T^2(l\gamma, \not{E}_T) = [(M_{l\gamma}^2 + |\vec{p_T}(l)+\vec{p_T}(\gamma)|^2)^{1/2} + \not{E}_T]^2 - |\vec{p_T}(l)+\vec{p_T}(\gamma)+\vec{\not{E}}_T|^2$

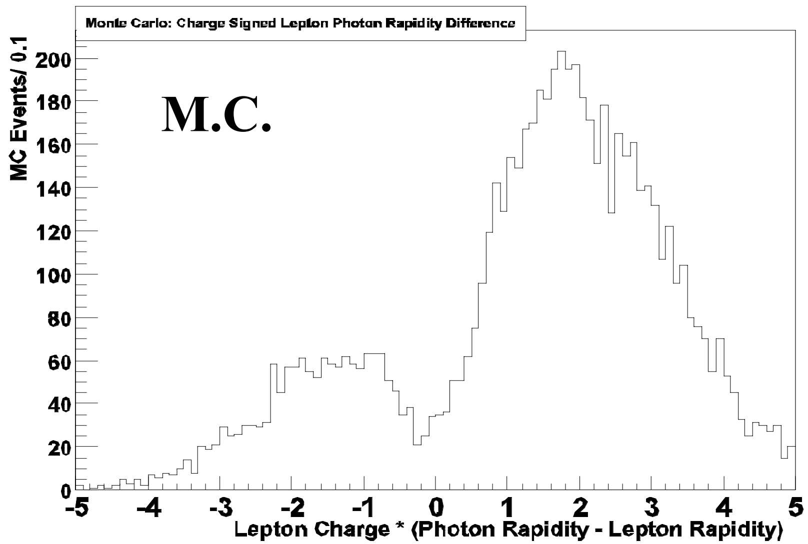




Wγ Radiation Amplitude Zero

- For COS(θ*), the angle between incoming quark and photon in the Wγ rest frame, = –1/3, SM has “amplitude zero”.
- For events w/ M_T(cluster)>90 GeV/c^2. One could guess the Wγ rest frame. We use charge-signed $\Delta\eta(l,\gamma)$





- We plot the background-subtracted muon data vs. MC $\Delta\eta(l,\gamma)$ => hints of the Rad. Zero.
- It will help to extend the eta-coverage of electrons and especially of photons.