Di-boson physics from the Tevatron

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for the CDF and DØ Collaborations

XLII$^{\text{èmes}}$ Rencontres de Moriond,
Electroweak session, La Thuile, March 10-17, 2007

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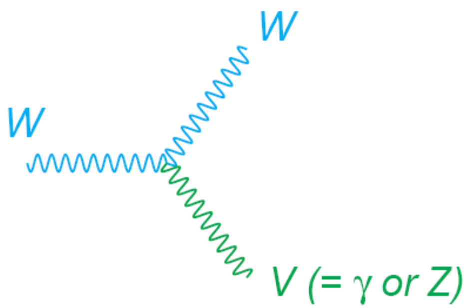
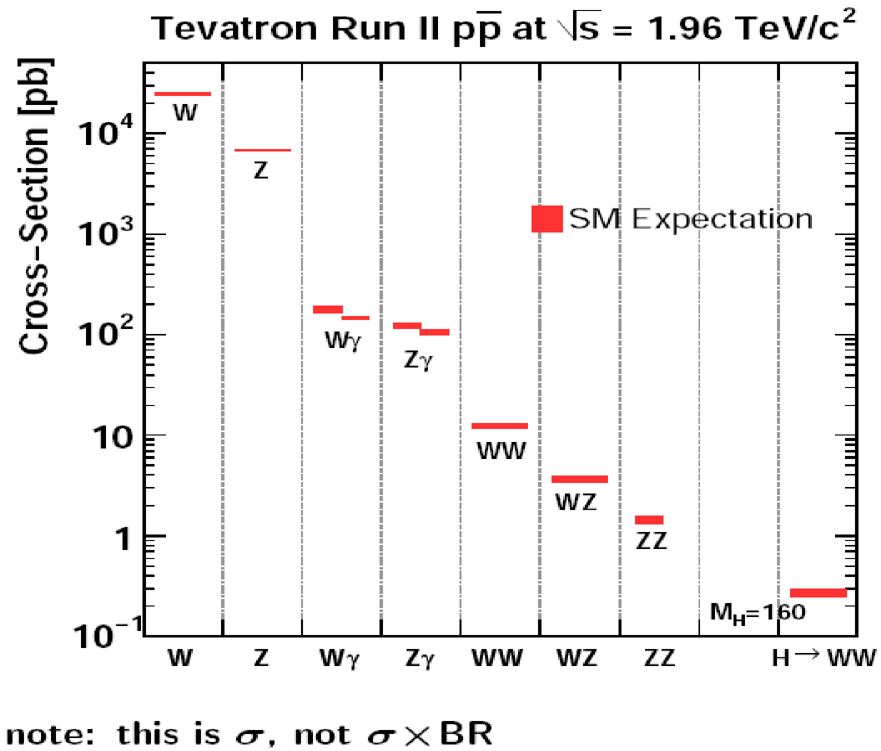
Motivation



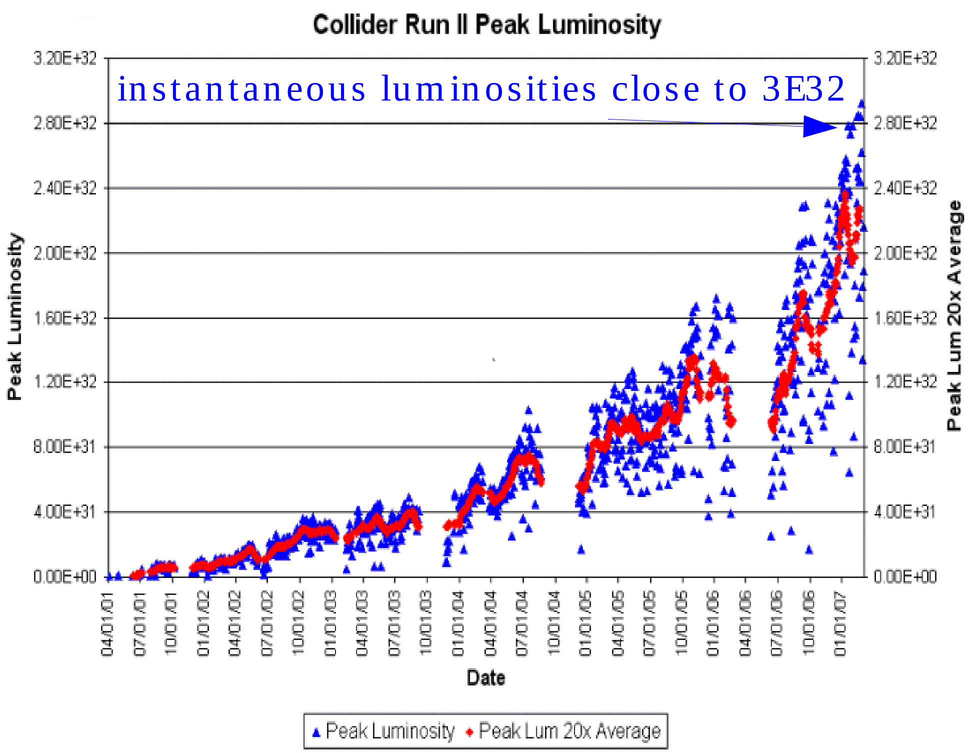
- Probing Non-Abelian structure of SM: test of Triple Gauge Couplings
- Stringent limits from LEP but Tevatron is complementary:
  - explores higher centre of mass and p_T values
  - probes different coupling combinations than LEP
  - competitive with few fb^{-1}
- New physics probe (Anomalous Couplings)
- Background of numerous analyses (H -> WW, SUSY, t tbar)

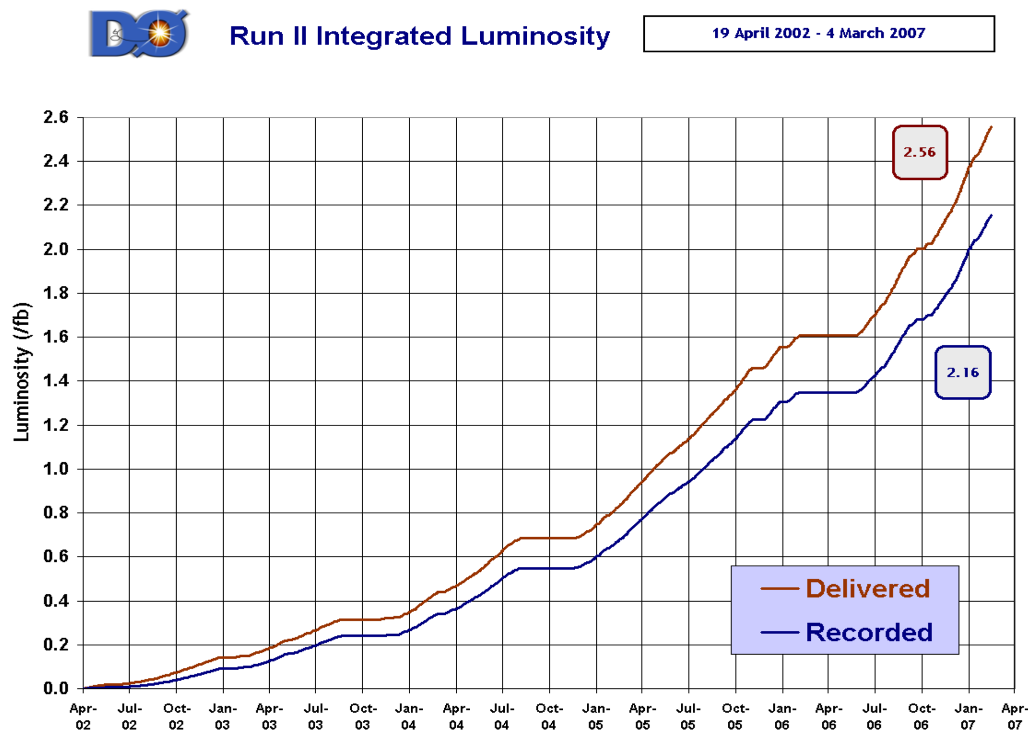
At 10^{-2} to 10^{-4} of single production σ, too low statistics at Run I
=> low significance of diboson signal



Tevatron today

p – pbar collider at $\sqrt{s}$ = 1.96 TeV





Tevatron has delivered 2.5 fb^{-1}

CDF and DØ each have ~2.0 fb^{-1} on tape

Results shown here are using up to 1.1 fb^{-1}

"Tevatron is a boson factory"

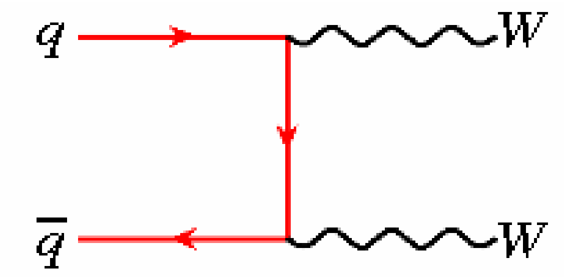
Selection criteria

Working in hadron collider environment => focus on the clean lepton channels.

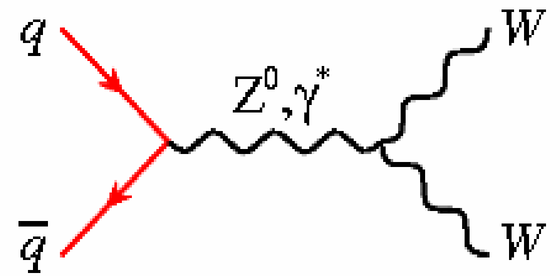
CDF and DØ have excellent lepton ID capabilities
... and hermetic calorimeters to measure missing E_T (=> infer presence of neutrino)

- **electrons**
  - E_t above $\approx$20 GeV
  - shower shape criteria
  - isolation requirement
  - $|\eta|$ coverage CDF $<$1.1 (central), 1.2–2.0 (forward)
    DØ $<$1.1 (central), 1.5–2.5 (forward)
- **muons**
  - p_t above $\approx$20 GeV
  - isolation requirement
  - $|\eta|$ coverage CDF $<$1.1/1.2 (central)
    DØ $<$1 (central), 1–2 (forward)
- **neutrinos**
  - missing E_t above $\approx$20 GeV
  - CDF: isolation requirement (angular distance)

WW



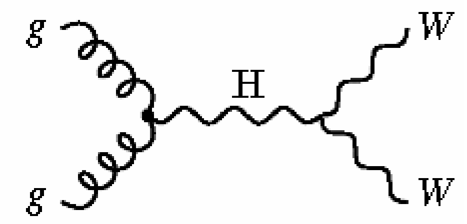
t channel ~ 90 %



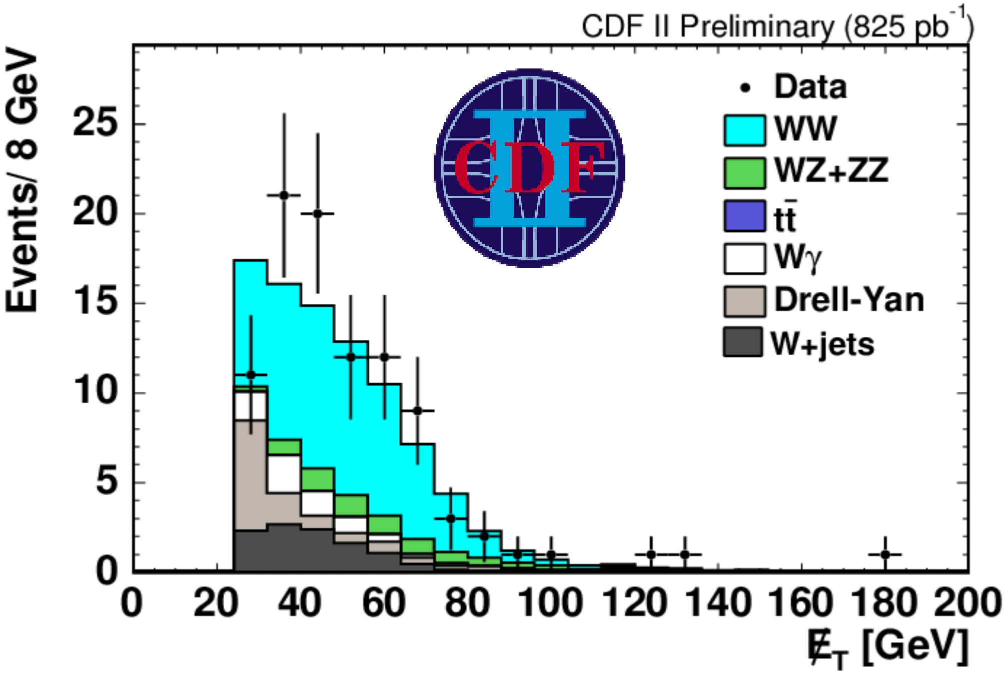
s channel ~ 10 %

Sensitive to WWZ / WWγ

Also an important background for a possible high-mass Higgs:



Dilepton analysis: ee, μμ, eμ
- clean, but low branching fraction
- two isolated high-p_T leptons of opposite charge
- veto same-flavour combinations consistent with Z mass
- large missing E_T (2 ν)



WW cross section results

CDF ($825\ pb^{-1}$) | DØ ($224-252\ pb^{-1}$)

Process	CDF ee	CDF μμ	CDF eμ	DØ ee	DØ μμ	DØ eμ
WW signal	12.8 ± 0.1 ± 1.1	10.7 ± 0.1 ± 0.9	28.8 ± 0.1 ± 2.4	3.42 ± 0.05	2.10 ± 0.05	11.10 ± 0.10
Total BKG	15.2 ± 0.6 ± 1.7	7.8 ± 0.4 ± 1.0	14.8 ± 0.6 ± 2.3	2.30 ± 0.21	1.95 ± 0.41	3.81 ± 0.17
Observed	29	19	47	6	4	15

CDF: $\sigma(p\ \bar{p} \to W^+W^-) = 13.6 \pm 2.3\ (stat) \pm 1.6\ (syst) \pm 1.2\ (lumi)$

preliminary

[see also: PRL 94, 211801 (2005)]

DØ: $\sigma(p\ \bar{p} \to W^+W^-) = 14.6\ ^{+5.8}_{-5.1}\ (stat)\ ^{+1.8}_{-3.0}\ (syst) \pm 0.9\ (lumi)$

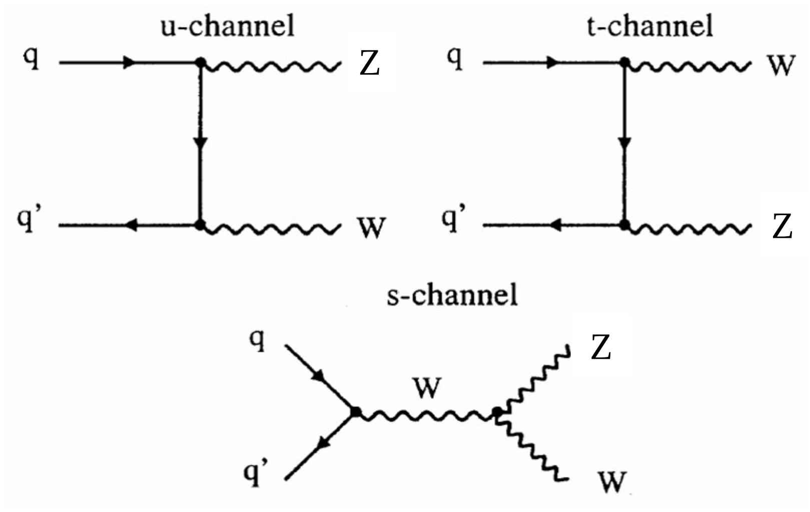
PRL 94, 151801 (2005)

- **Run II WW signal clearly established**
- **Good agreement with NLO SM prediction:**

12.4±0.8 pb

WZ

- Sensitive to WWZ vertex
  - cf. WW production, which depends on WWZ ***and*** WW**γ**
  - Allows study of WWZ coupling parameters with ***no assumptions*** about WW**γ** couplings
  - unavailable at LEP
- SM cross section is 3.7 pb (J.M Campbell and R.K. Ellis)
- WZ $\rightarrow l \nu l^+ l^-$ mode is clean and unambiguous
  - but has low branching fraction 1.5%



Z selection:

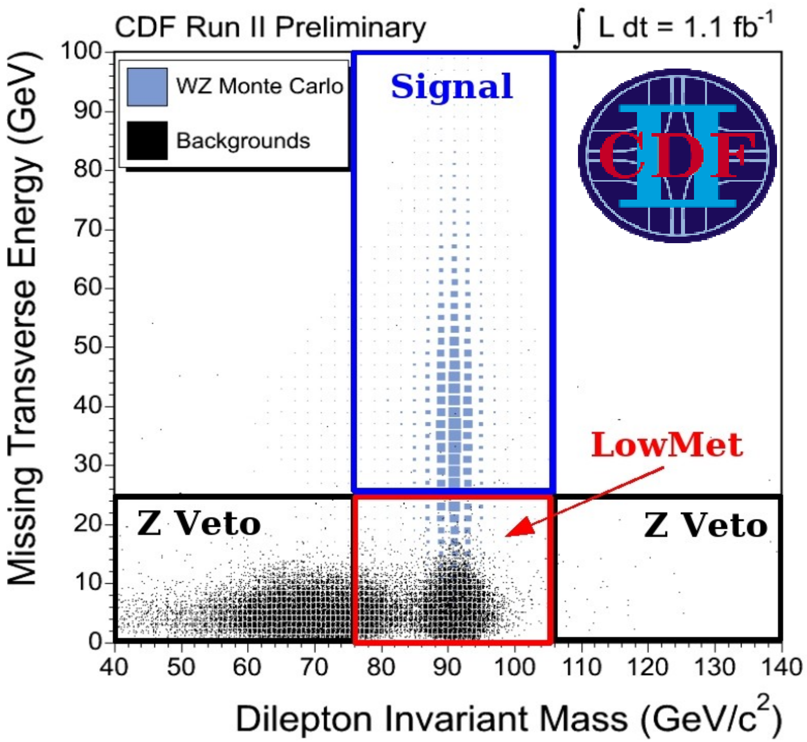
- 2 high P_T leptons (ee or $\mu\mu$)
- M_{inv} (ll) consistent with M_Z

W selection:

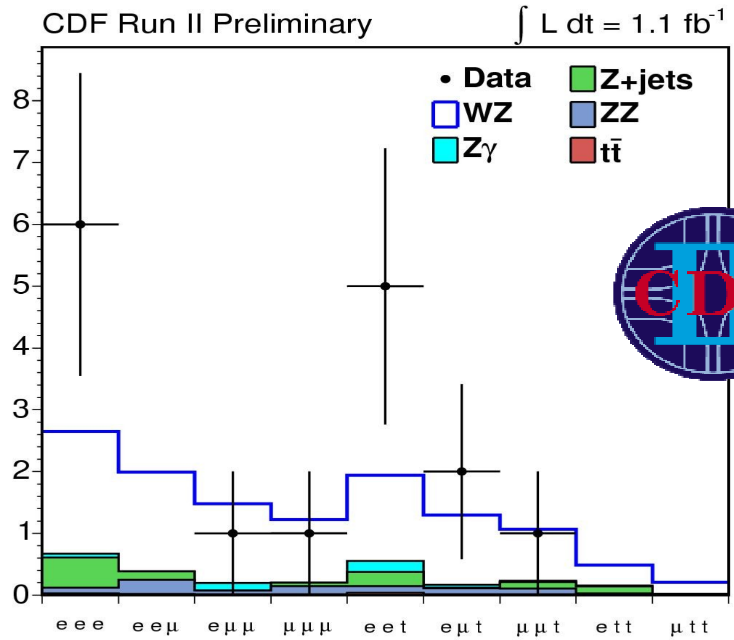
- isolated lepton + E_T Miss

Main backgrounds:

- Z/γ^* + jet
- ZZ



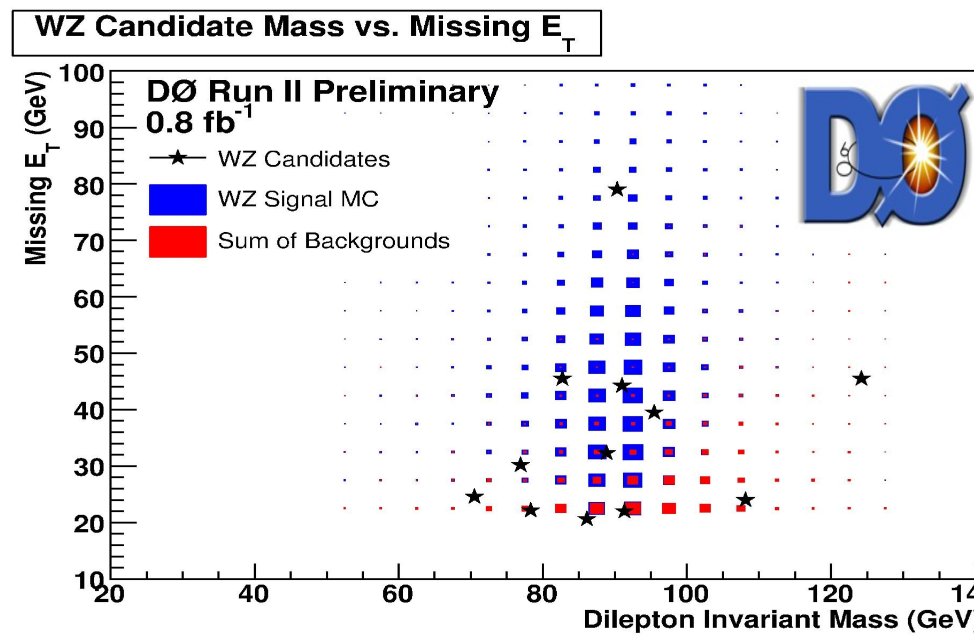
WZ observation



Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	1.22 ± 0.27 ± 0.28 ± -
ZZ	0.89 ± 0.01 ± 0.09 ± 0.05
$Z\gamma$	0.48 ± 0.06 ± 0.15 ± 0.03
$t\bar{t}$	0.12 ± 0.01 ± 0.01 ± 0.01
WZ	9.79 ± 0.03 ± 0.31 ± 0.59
Total Background	2.70 ± 0.28 ± 0.33 ± 0.09
Total Expected	12.50 ± 0.28 ± 0.46 ± 0.68
Observed	**16**

Cross section:

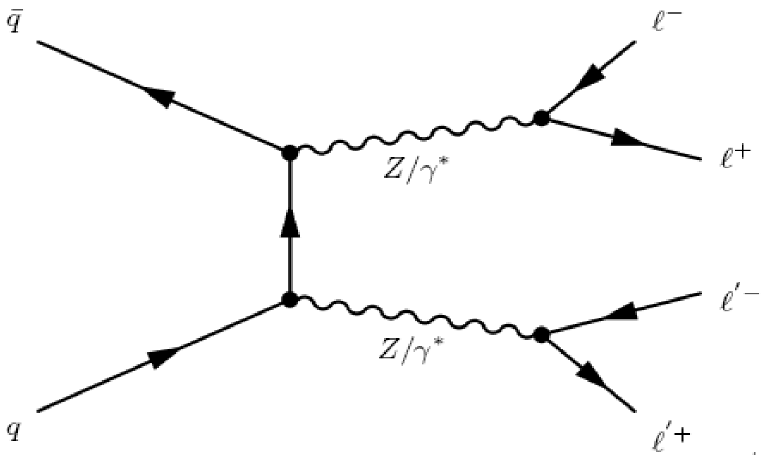
	measured	predicted	signal significance
CDF	$5.0^{+1.8}_{-1.4}$(stat)±0.4(syst) pb	3.7±0.3 pb	6.0 σ
DØ	$4.0^{+1.9}_{-1.5}$(stat+syst) pb	3.7±0.3 pb	3.3 σ



Observed !

... and found to be consistent with SM predictions

ZZ



No self coupling of Z bosons in the standard model:

no ZZγ
no ZZZ

Low cross section in standard model.

Clean signature: four isolated leptons in the final state !

... but this also means that acceptance and efficiency are absolutely crucial

Our detectors/triggers have good angular coverage and efficiency.
Here is the example of the acceptance/efficiency for the eeμμ channel in the DØ analysis:

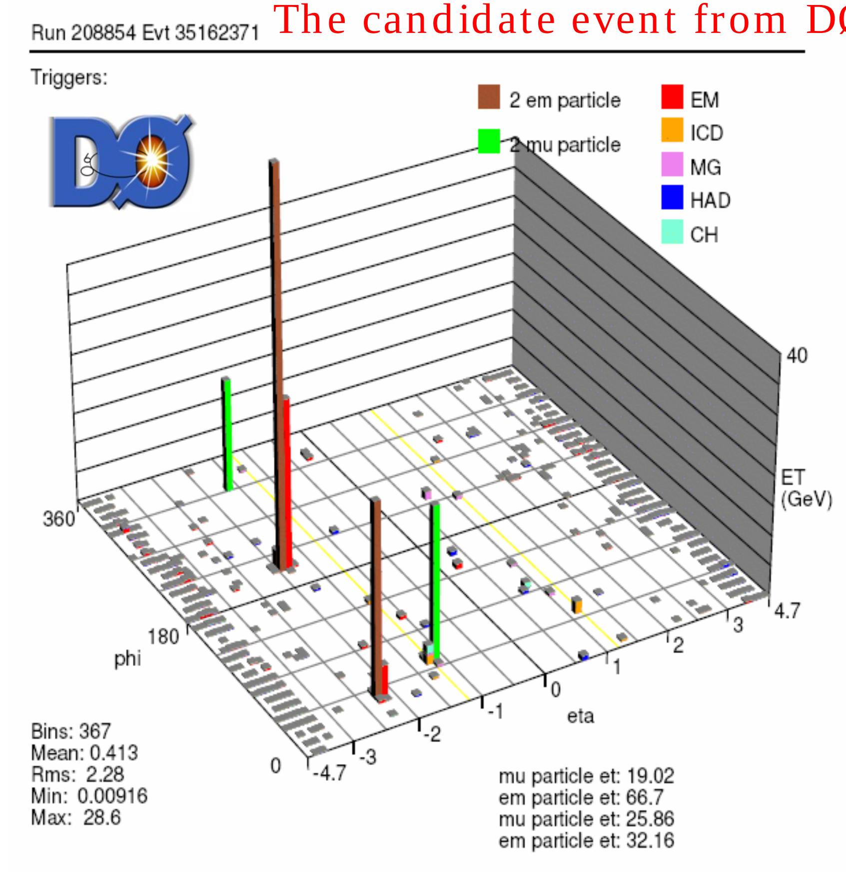
Selection	Exclusive Acceptance	Cumulative Acceptance
geometric cuts	0.560 ± 0.006	0.560 ± 0.006
electron and muon separation $R > 0.2$	0.982 ± 0.001	0.550 ± 0.006
$p_T > 15$ GeV	0.780 ± 0.010	0.429 ± 0.007
trigger	0.990 ± 0.010	0.425 ± 0.008
electron and muon quality cuts	0.514 ± 0.046	0.218 ± 0.030
total		0.218 ± 0.030

ZZ cross section limits

Channel	Luminosity	Acceptance	Background	Signal	N
$\mu\mu\mu\mu$	$(944 \pm 61)\text{pb}^{-1}$	0.27 ± 0.024	0.057 ± 0.017	0.47 ± 0.05	0
$eeee$	$(1070 \pm 70)\text{pb}^{-1}$	0.23 ± 0.01	0.080 ± 0.017	0.44 ± 0.04	0
$\mu\mu ee$	$(1020 \pm 66)\text{pb}^{-1}$	0.22 ± 0.019	0.034 ± 0.014	0.81 ± 0.09	1
Total			0.17 ± 0.04	1.71 ± 0.11	1

Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	$0.007 \pm 0.007 \pm 0.004 \pm$ -
$Z\gamma\gamma$	$0.002 \pm 0.001 \pm 0.000 \pm 0.000$
ZZ	$1.884 \pm 0.015 \pm 0.061 \pm 0.113$
Total Background	$0.009 \pm 0.007 \pm 0.004 \pm 0.000$
Total Expected	$1.893 \pm 0.017 \pm 0.062 \pm 0.113$
Observed	**1**

The candidate event from DØ:



We set the following limits:

CDF: $\sigma(ZZ) < 3.8$ pb (95%CL)

DØ: $\sigma(ZZ) < 4.3$ pb (95%CL)

Consistent with standard model value: 1.4 ± 0.1 pb

With 4 - 8 fb^{-1}, this could become another first observation.

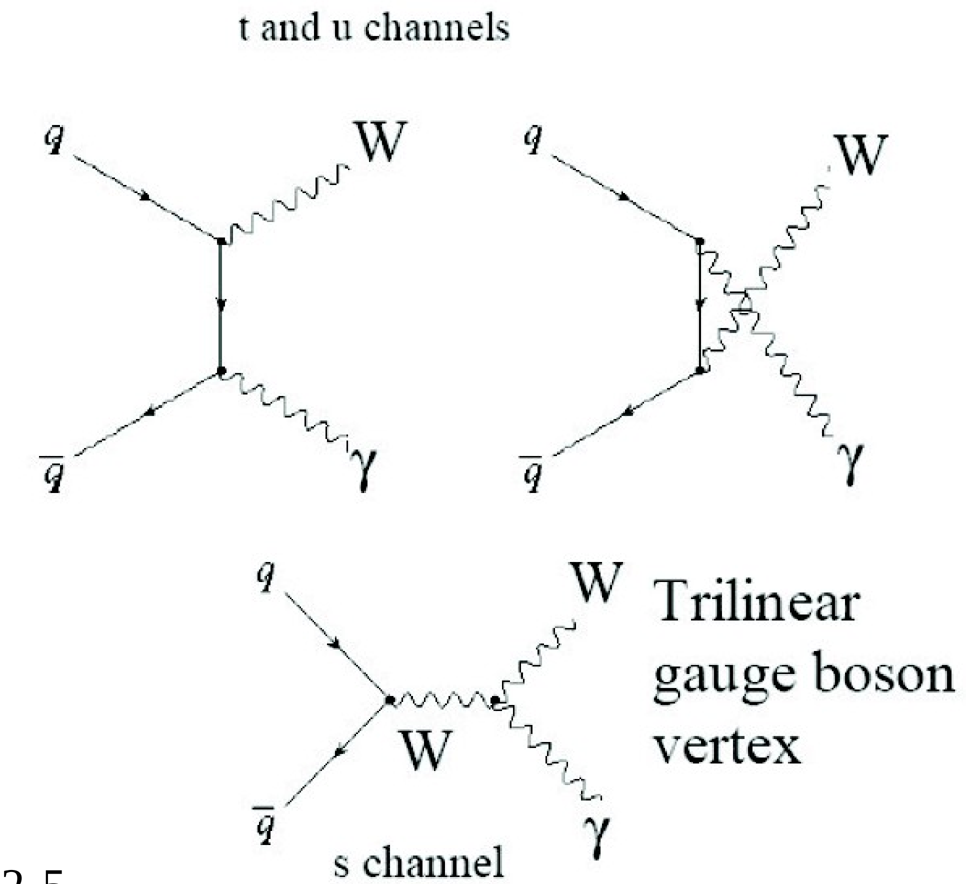
$W\gamma$

Sensitive to $WW\gamma$ coupling

Couplings at interaction vertices are fixed in standard model gauge theory

Variation in $W\gamma$ production would be sign of new physics

e.g. changes in $p_T(\gamma)$ spectrum,
in particular at high $M_T(W\gamma)$



γ ID is crucial

CDF: $E_T > 7$ GeV, $|\eta| < 1.1$

DØ: $E_T > 7$ GeV, $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$

Both analyses: photon well separated from lepton: $\text{deltaR}(l,\gamma) > 0.7$

Experimental challenges:
- background due to "π^0- like jets" faking photons (e.g.: in contrast to electrons, no track- matching)
- no simple standard candle that would provide clean control sample of isolated high- p_T photons (like $Z \rightarrow e\, e$ for electrons)

Wγ signal

Yields in the DØ analysis

	Muon Channel	Electron Channel
Luminosity	878 pb^{-1}	933 pb^{-1}
W + jet Background Events	98 ± 12 (stat. + sys.)	148 ± 17 (stat. + sys.)
ℓeX Background Events	6 ± 2 (stat. + sys.)	34 ± 4 (stat. + sys.)
$W\gamma \to \tau\nu\gamma$ Background Events	2.6 ± 0.4 (stat. + sys.)	1.7 ± 0.2 (stat. + sys.)
$Z\gamma \to \ell\ell\gamma$ Background Events	8 ± 1 (stat. + sys.)	-
Candidate Events	245	389
Expected Signal	130 ± 9	211 ± 14
Measured Signal	130 ± 18	205 ± 26

DØ preliminary (0.9 fb^{-1}): $E_T(\gamma) > 7$ GeV, deltaR(l,γ) > 0.7, $M_T(l\gamma\nu) > 90$ GeV:

muon channel: $\sigma(p\,\bar{p} \to l\,\nu\,\gamma\,X) = 3.21 \pm 0.49$ (stat+sys) ± 0.19 (lum) pb

electron channel: $\sigma(p\,\bar{p} \to l\,\nu\,\gamma\,X) = 3.12 \pm 0.49$ (stat+sys) ± 0.20 (lum) pb

theory: $\sigma(p\,\bar{p} \to l\,\nu\,\gamma\,X) = 3.21 \pm 0.08$ (PDF) pb

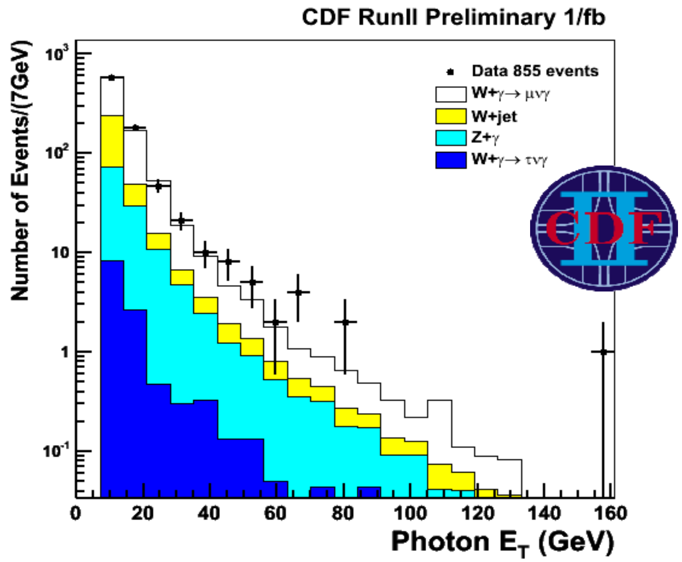
CDF preliminary (1.1 fb^{-1}): $E_T(\gamma) > 7$ GeV, deltaR(e,γ) > 0.7, $30 < M_T(\mu\nu) < 120$ GeV:

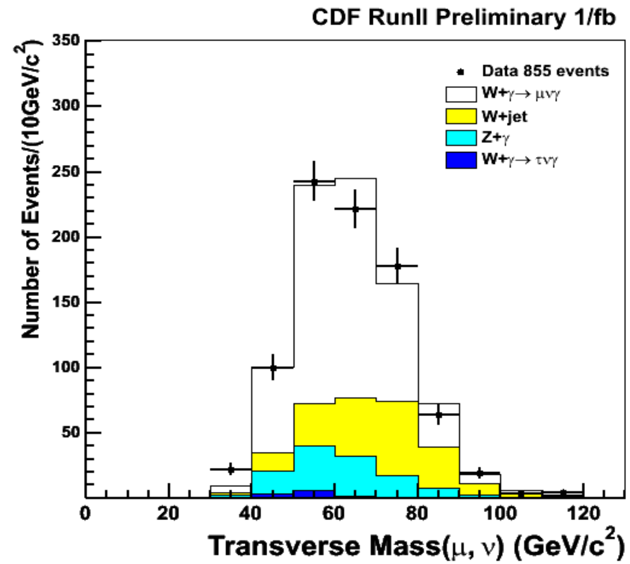
muon channel: $\sigma(p\,\bar{p} \to \mu\,\nu\,\gamma\,X) = 19.11 \pm 1.04$ (stat) ± 2.40 (sys) ± 1.11 (lum) pb

theory: $\sigma(p\,\bar{p} \to \mu\,\nu\,\gamma\,X) = 19.3 \pm 1.4$ (sys) pb

Measured cross sections and photon E_T spectra are in good agreement with standard model predictions.

Example plots from the CDF analysis

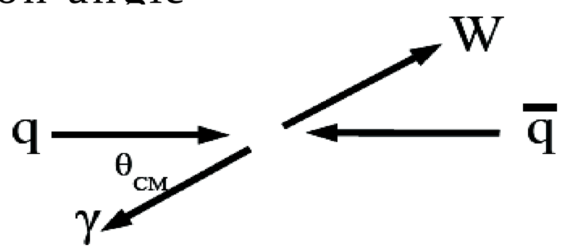




Wγ: radiation amplitude zero

Increased sensitivity to anomalous couplings through charge-signed rapidity difference:

Standard model couplings at LO produce an amplitude zero in the centre-of-mass production angle

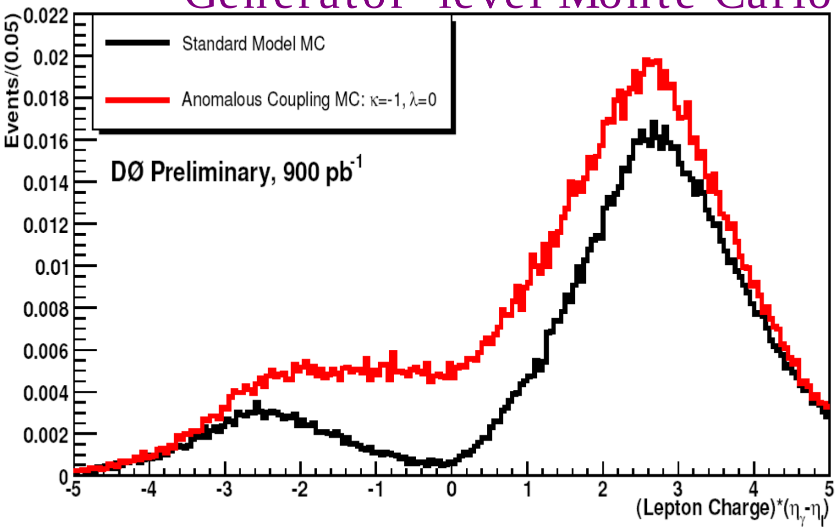


$u\bar{d} \to W^+\gamma$ has zero at $\cos\theta_{CM} = -1/3$

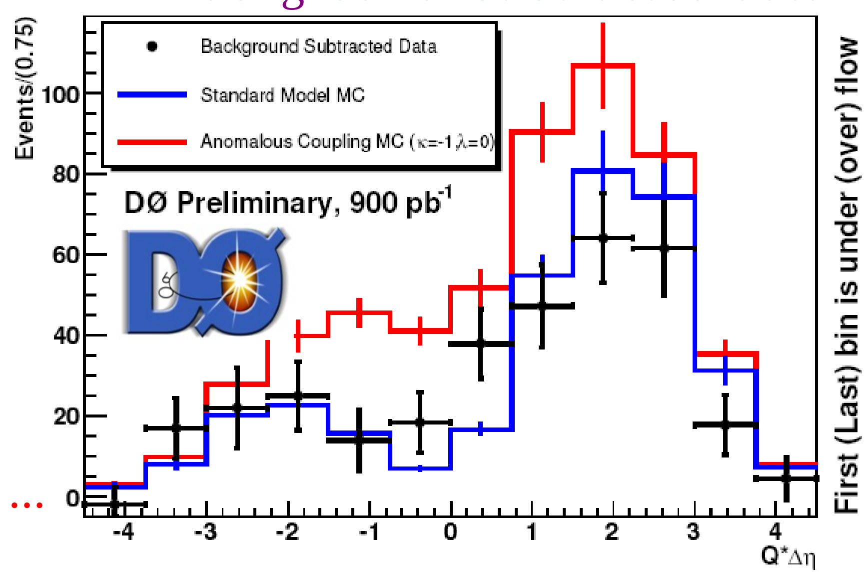
$d\bar{u} \to W^-\gamma$ has zero at $\cos\theta_{CM} = +1/3$

Correlations lead to dip in $\gamma\ell$ charge-sign rapidity difference

Generator-level Monte Carlo



Background-subtracted data



DØ data in good agreement with standard model …

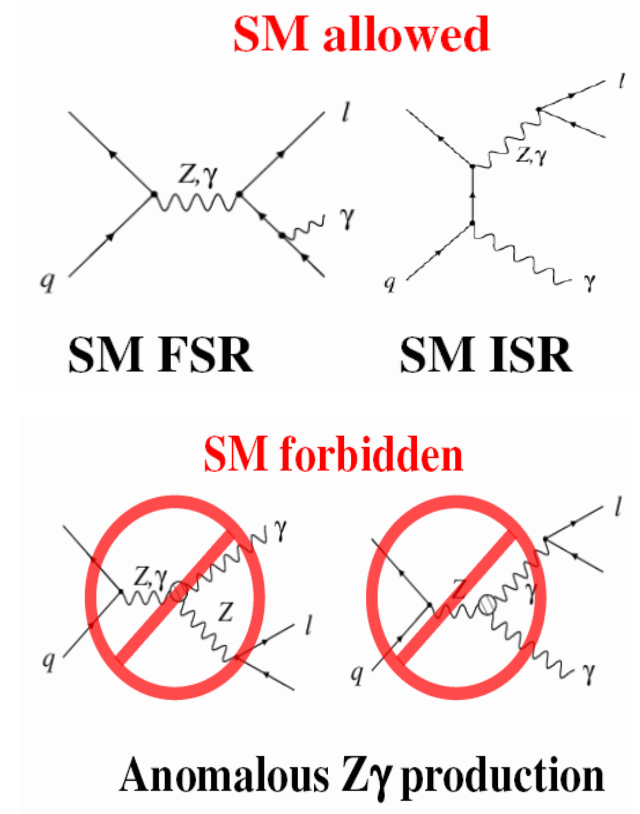
… looking forward to even more data !

Zγ

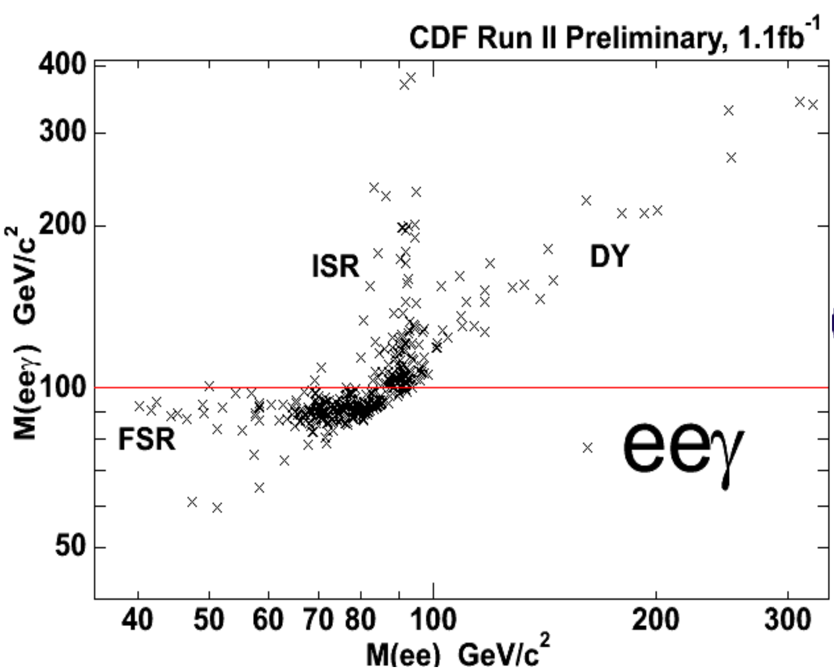
For example in 1.1 fb^{-1} of CDF data
(similar analysis performed at DØ):

Require

- two high-p_T electrons (E_T > 20 GeV, |eta| < 2.8)
- a high-p_T photon (E_T > 7 GeV, |eta| < 1.1)
  well separated from the electrons: deltaR(e,γ) > 0.7



Anomalous ZZγ and Zγγ couplings
(appear in extensions of SM)
can increase rate for high-p_T photons.



Zgamma events yields Luminosity 1 fb^{-1}	$M_{ee\gamma}$ > 40 GeV	$M_{ee\gamma}$ > 100 GeV (ISR dominate)
signal MC	323.8 ± 17.3	117.2 ± 6.3
Background	51.0 ± 15.7	39.2 ± 12.4
total SM+BG	374.8 ± 23.4	156.4 ± 13.9
Data	390	154

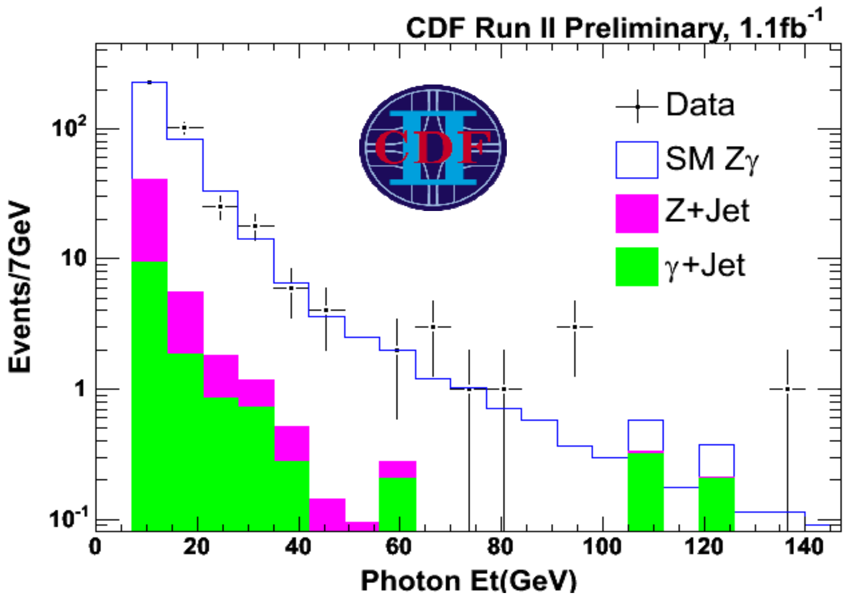
Zγ: cross section, event properties

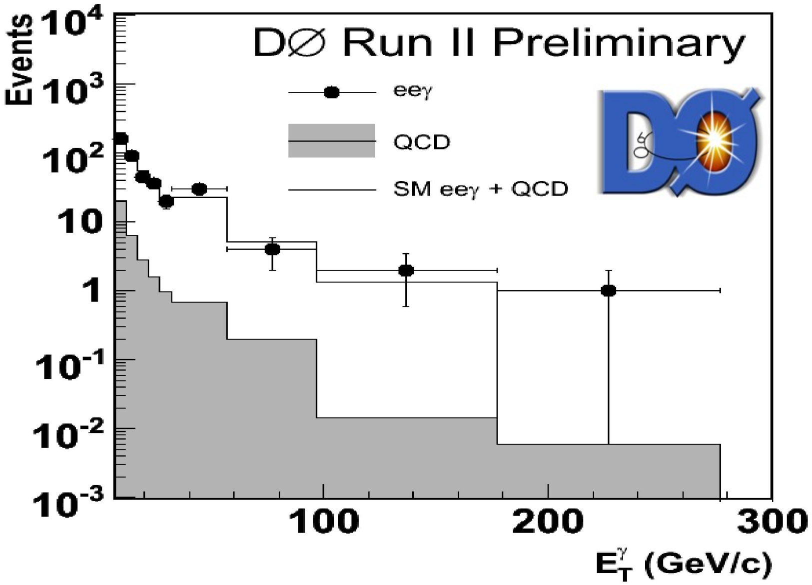
CDF preliminary (1.1 fb^{-1}):

$E_T(\gamma) > 7$ GeV, deltaR(e,γ) > 0.7, M(eeγ) > 40 GeV:	σ(Zγ) * BR(Z→ll) = 4.9 ± 0.3 (stat) ± 0.3 (sys) ± 0.3 (lum) pb
theory:	σ(Zγ) * BR(Z→ll) = 4.7 ± 0.4 (sys) pb
$E_T(\gamma) > 7$ GeV, deltaR(e,γ) > 0.7, M(eeγ) > 100 GeV:	σ(Zγ) * BR(Z→ll) = 1.4 ± 0.1 (stat) ± 0.2 (sys) ± 0.1 (lum) pb
theory:	σ(Zγ) * BR(Z→ll) = 1.4 ± 0.1 (sys) pb

DØ preliminary (1.0 fb^{-1}):

$E_T(\gamma) > 7$ GeV, deltaR(e,γ) > 0.7, M(ee) > 30 GeV:	σ(Zγ) * BR(Z→ll) = 4.51 ± 0.37 (stat+sys) ± 0.27 (lum) pb
theory (NLO, Baur, Han, Ohnemus):	σ(Zγ) * BR(Z→ll) = 4.2 ± 0.2 (sys) pb

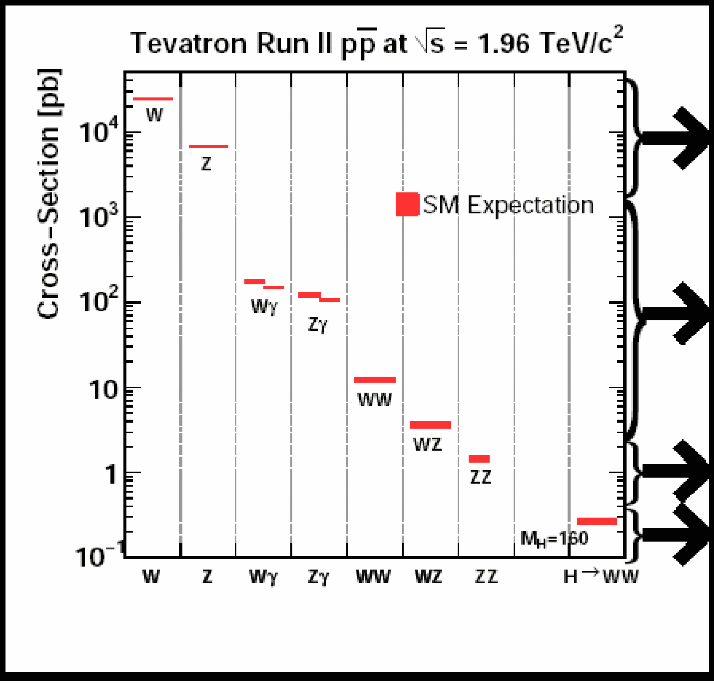




Measured cross sections and photon E_T spectra are in good agreement with standard model predictions.

Conclusions

- DØ+CDF data samples increase quickly
- understanding of detector response improving as well
- bringing electroweak precision physics to the ~~next~~ next-to-next level!



- precision physics playground
- established signals — more data should help to improve those!
- promising searches
- ?

For more detailed documentation:

http://www-cdf.fnal.gov/physics/ewk/

http://www-d0.fnal.gov/Run2Physics/WWW/results/ew.htm