First Observation of WZ Production and Search for ZZ at CDF

Mark Neubauer

University of California, San Diego

for the CDF Collaboration

Physics Motivation: Dibosons

Probe non-Albelian nature of $SU(2)_L \otimes U(1)_Y$

→ Gauge boson self-interactions

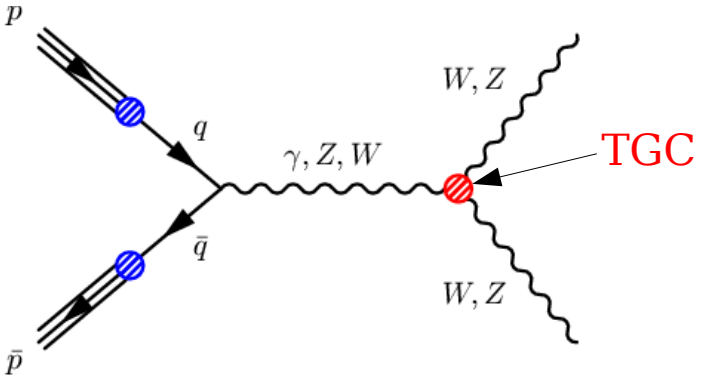
- Diboson production sensitive to new physics (NP) in trilinear gauge couplings (TGC)

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

- Sensitive to different TGC combinations
- Tevatron explores higher $\hat{s}$ than LEP

Experimentalist perspective:

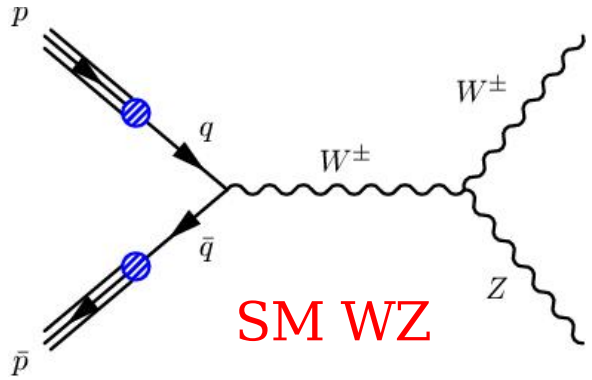
- Dibosons are an important background for many high p_T analyses (H→WW*, ZH/WH, SUSY, $t\bar{t}$, ...)
- Demonstrate sensitivity to NP in multilepton final states



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

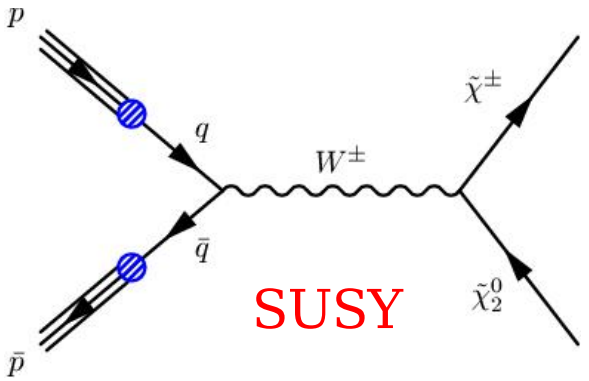
Absent in SM

$p\bar{p} \to W^{\pm}Z^0 \to \ell^{\pm}\ell^+\ell^- + \not{E}_T$



SM WZ

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



SUSY

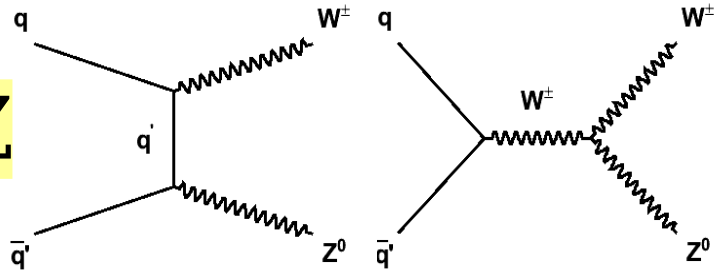
Wγ: Talk by A. Nagano
Zγ: Talk by J. Deng

Higgs / SUSY / ??? may be hiding somewhere in our diboson samples...

WZ/ZZ Production in the Standard Model

WZ

Involves a single SM triple gauge coupling:

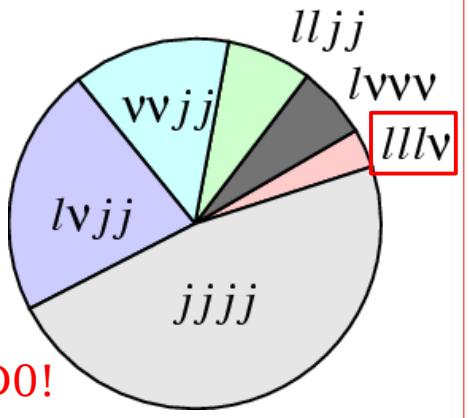


NLO cross section: 3.7 ± 0.1 pb

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

- Not available @ LEP
- Measure WWZ coupling independent of WWγ
- Yet to be observed (>5σ)

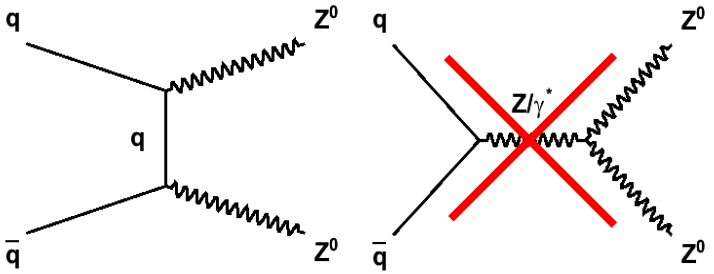
First evidence (3.3σ) from D0!
(see talk by J.Degenhardt)



BR(WZ → 3 e,μ) = 1.8%

ZZ

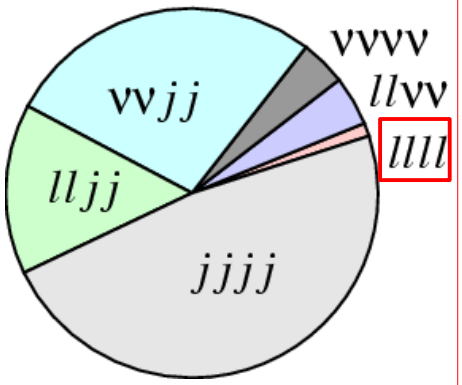
Triple neutral gauge couplings absent in SM:



NLO cross section: 1.4 ± 0.1 pb

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

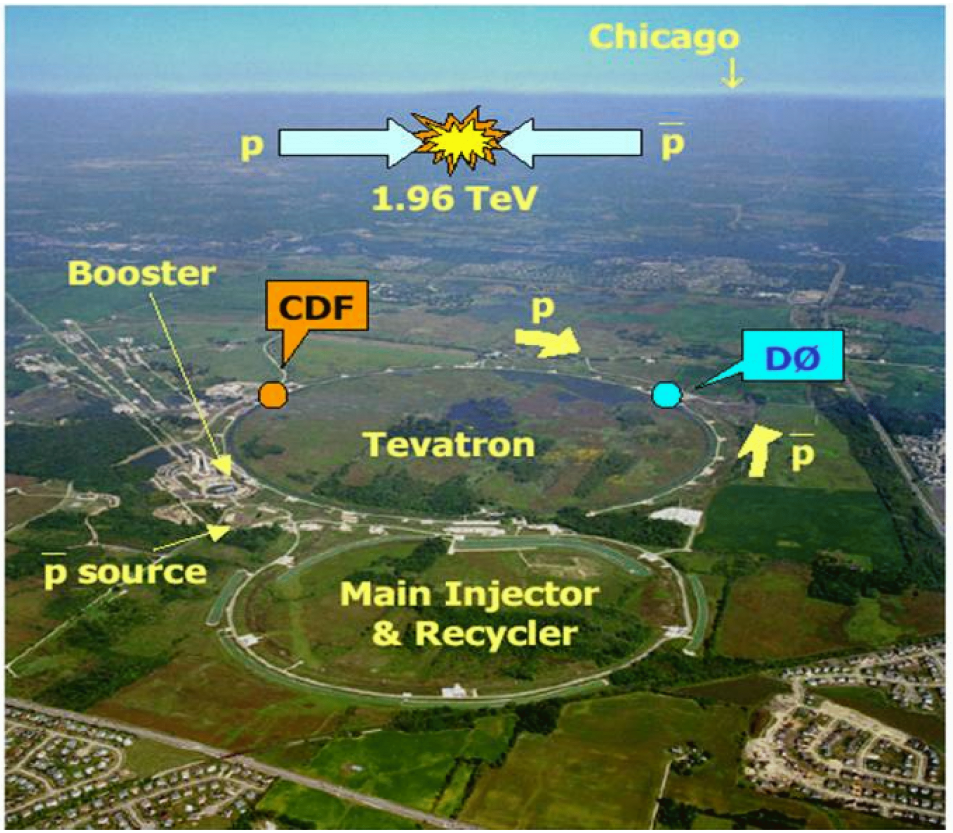
- Search for ZZγ or ZZZ coupling (=0 in SM)
- SM ZZ production not yet observed in $p\bar{p}$

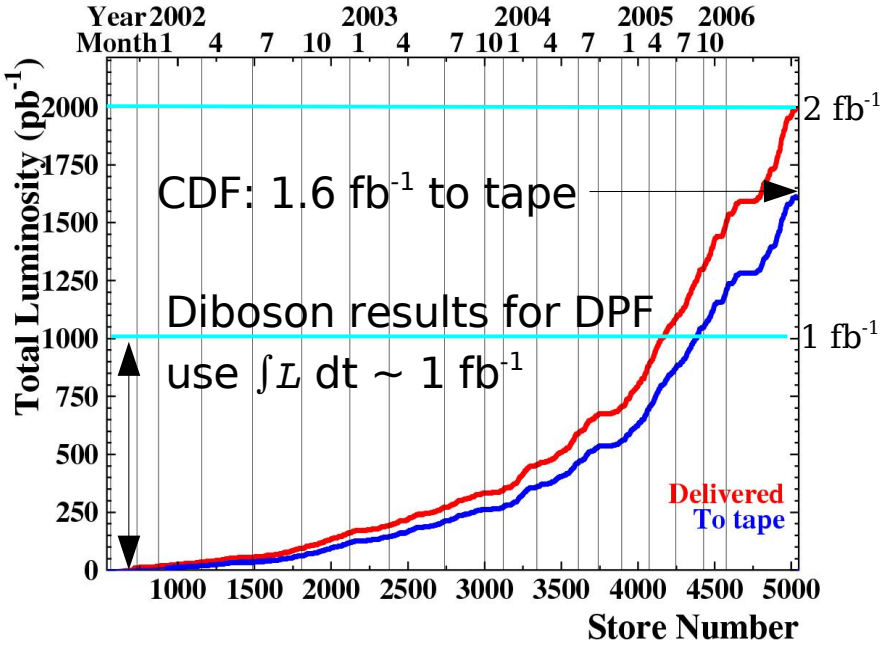


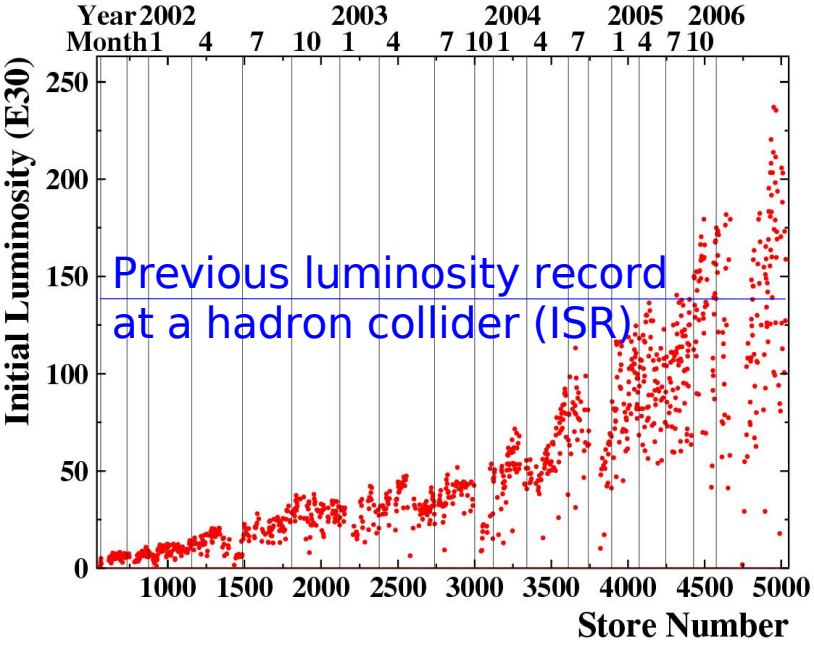
BR(ZZ → 4 e,μ) = 0.5%

The Fermilab Tevatron

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





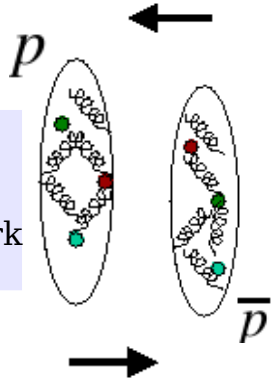


Run II Started 2001:

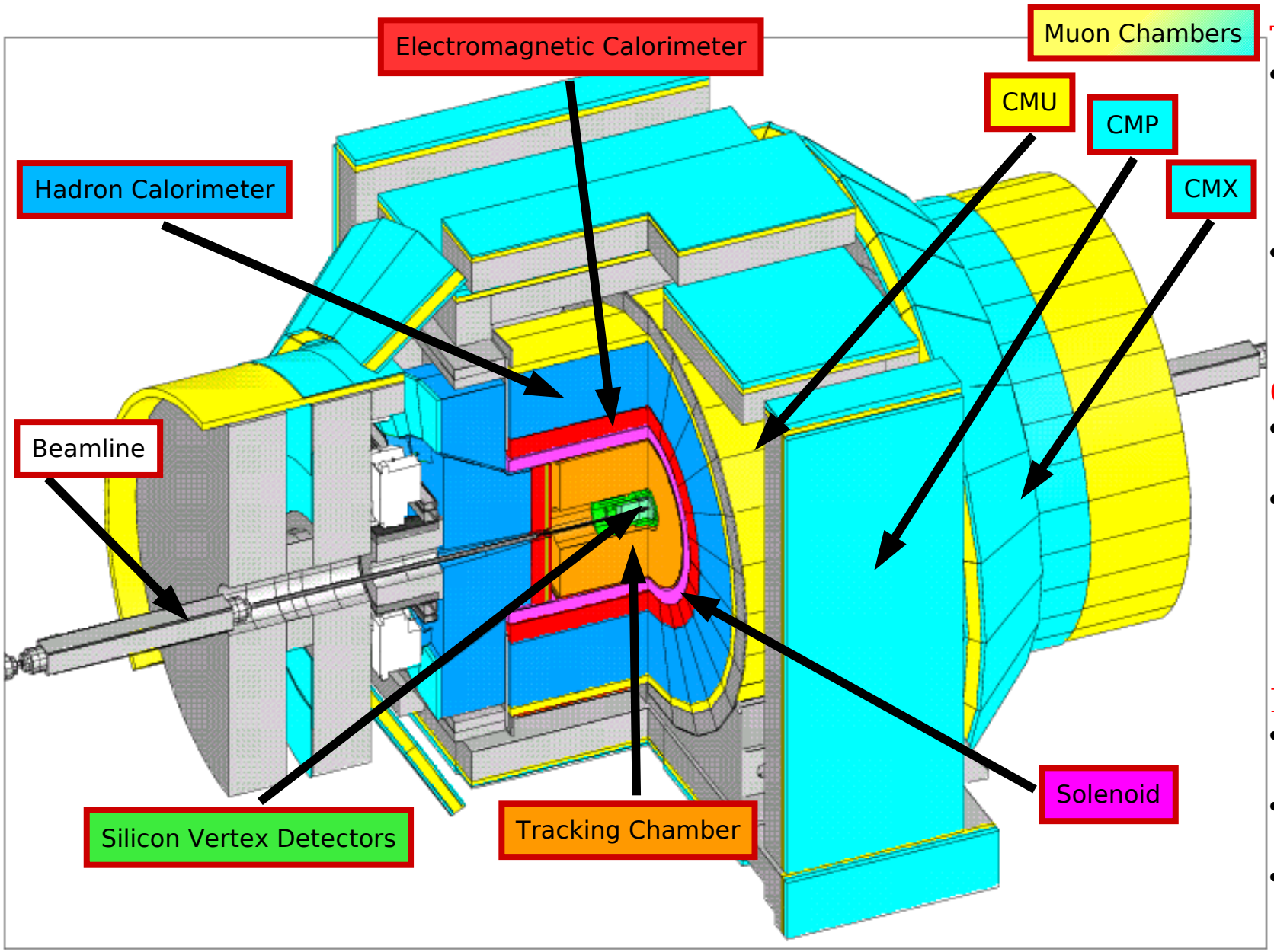
- $\sqrt{s}$=1.96 TeV
- record luminosity:
  $L_{inst} = 237 \times 10^{30}$ cm^{-2}s^{-1}
- $\int L\,dt$ = ~2 fb^{-1}
  $\rightarrow$ 4 – 8 fb^{-1} expected by 2009

Collisions:

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



The CDF II Detector



Tracking

- Central drift chamber
  - Track acceptance: 100% of layers $|\eta| < 1$ 0% by $|\eta| < 2$
- Silicon coverage out to $|\eta| < 2$ for large $|\eta|$ tracking

Calorimetry

- Segmented sampling EM/Had calorimeters
- Shower maximum detectors
  - shape measurement
  - central (gas)
  - forward (scintillator)

Muon Detection

- CMU/CMP (Central) ($|\eta| < 0.6$)
- CMX (Extended) ($0.6 < |\eta| < 1.2$)
- BMU (Forward) ($1.2 < |\eta| < 1.5$)

Lepton Selection

In final states with 3 or more leptons (e.g. WZ and ZZ), lepton acceptance is key

- Try to use every track and electromagnetic shower found
- Exploit as much of the available information as possible for each candidate

Electrons

- Central calorimeter fiducial
- Forward calorimeter fiducial
  - With or w/o Si-based track

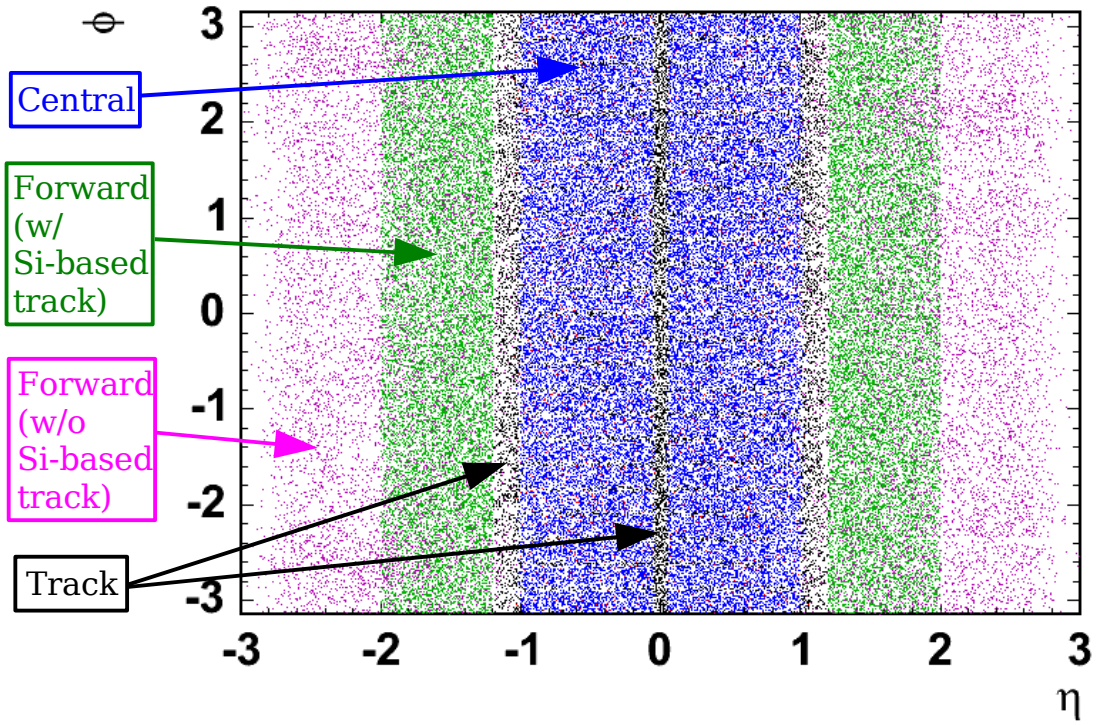
Muons

- CMU+CMP (CMUP) stubs
- CMX stub
- Minimum Ionizing Particle (MIP)

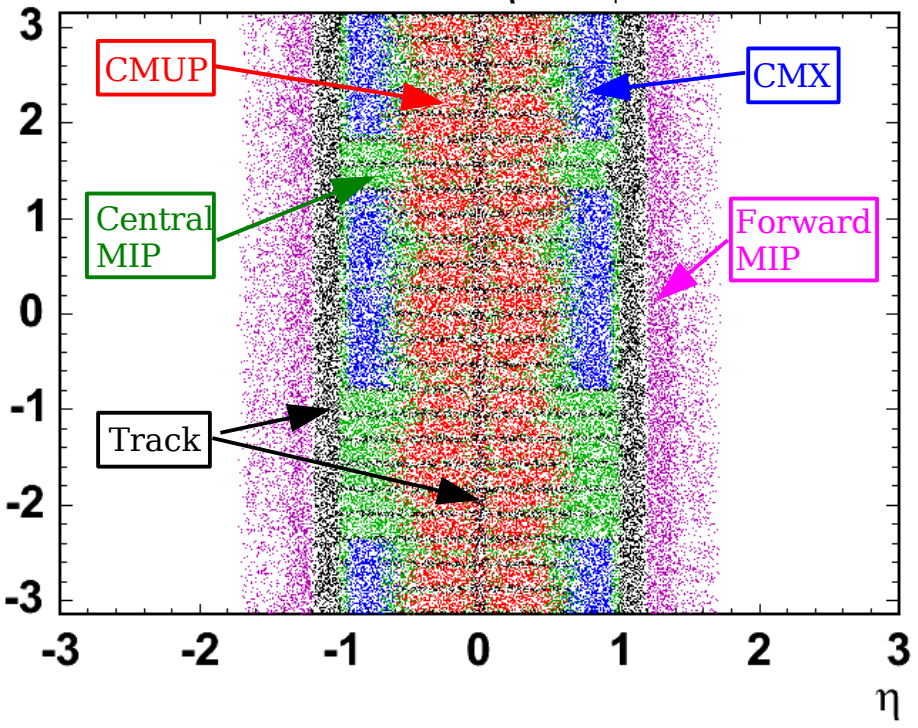
Tracks

- Fill in regions not fiducial to a calorimeter
- Considered flavor neutral (e or μ)

Electrons η vs. ϕ



Muons η vs. ϕ



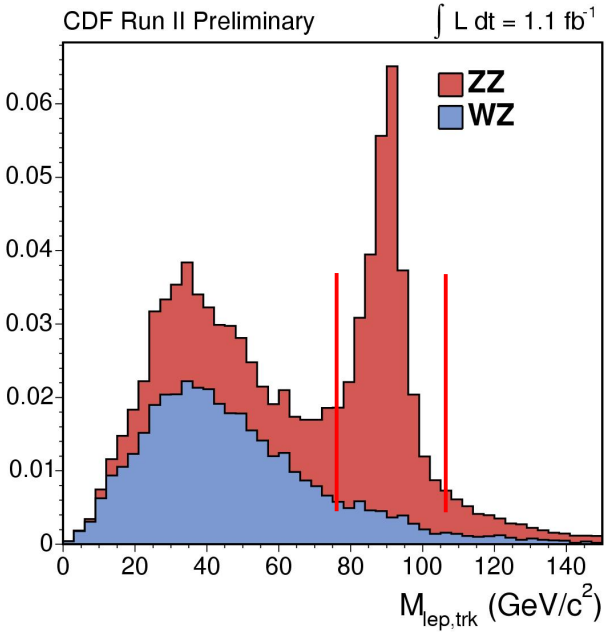
All leptons required to be calorimeter isolated: minimal transverse energy around lepton

WZ Selection

Background estimation:

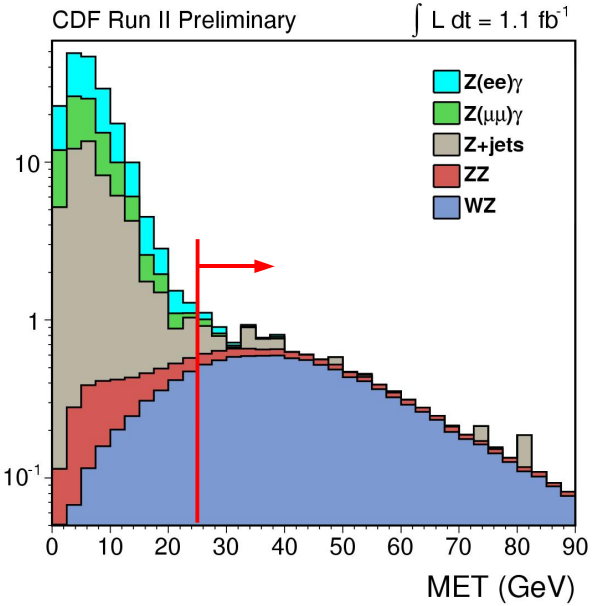
Expect backgrounds from $Z\gamma$, ZZ, Z+jets, $t\bar{t}$

- $Z\gamma$: U. Baur's ME generator + Pythia + GEANT
- ZZ, $t\bar{t}$: Pythia + GEANT
- Z+jets from data
  1) Measure P_{fake}(jet-like object $\rightarrow$ lepton) in inclusive jet data after correction for leptonic W,Z decays using MC
  2) Scale dilepton + jet-like object(s) events in data by P_{fake}



$W^{\pm}Z^{0} \rightarrow \ell^{\pm}\ell^{-}\ell^{+}\nu$ Selection:

- Triggers:
  Central $e^{\pm}$, Central $\mu^{\pm}$ (CMUP,CMX), Forward $e^{\pm}$ + large $\not\!\!E_T$
- 3 reconstructed leptons with E_T > 20,10,10 GeV
- Z region: ≥1 opp-sign, same flavor lepton pair in (76, 106)
- ZZ Veto: Invariant mass of non-Z ("W") lepton and an additional high p_T track (> 8 GeV) not in (76,106)
- $\Delta\phi(\not\!\!E_T$, nearest lepton or jet) > 9°
- $\not\!\!E_T$ > 25 GeV



WZ Control / Signal Regions

$W^{\pm}Z^{0} \rightarrow \ell^{\pm}\ell^{+}\ell^{-} + \not{E}_T$ Signal Region

- Z region ($76 < M_{\ell\ell} < 106$)
- $\not{E}_T > 25$ GeV

Dilepton (Drell-Yan) Region:

Tests efficiency and acceptance calculations

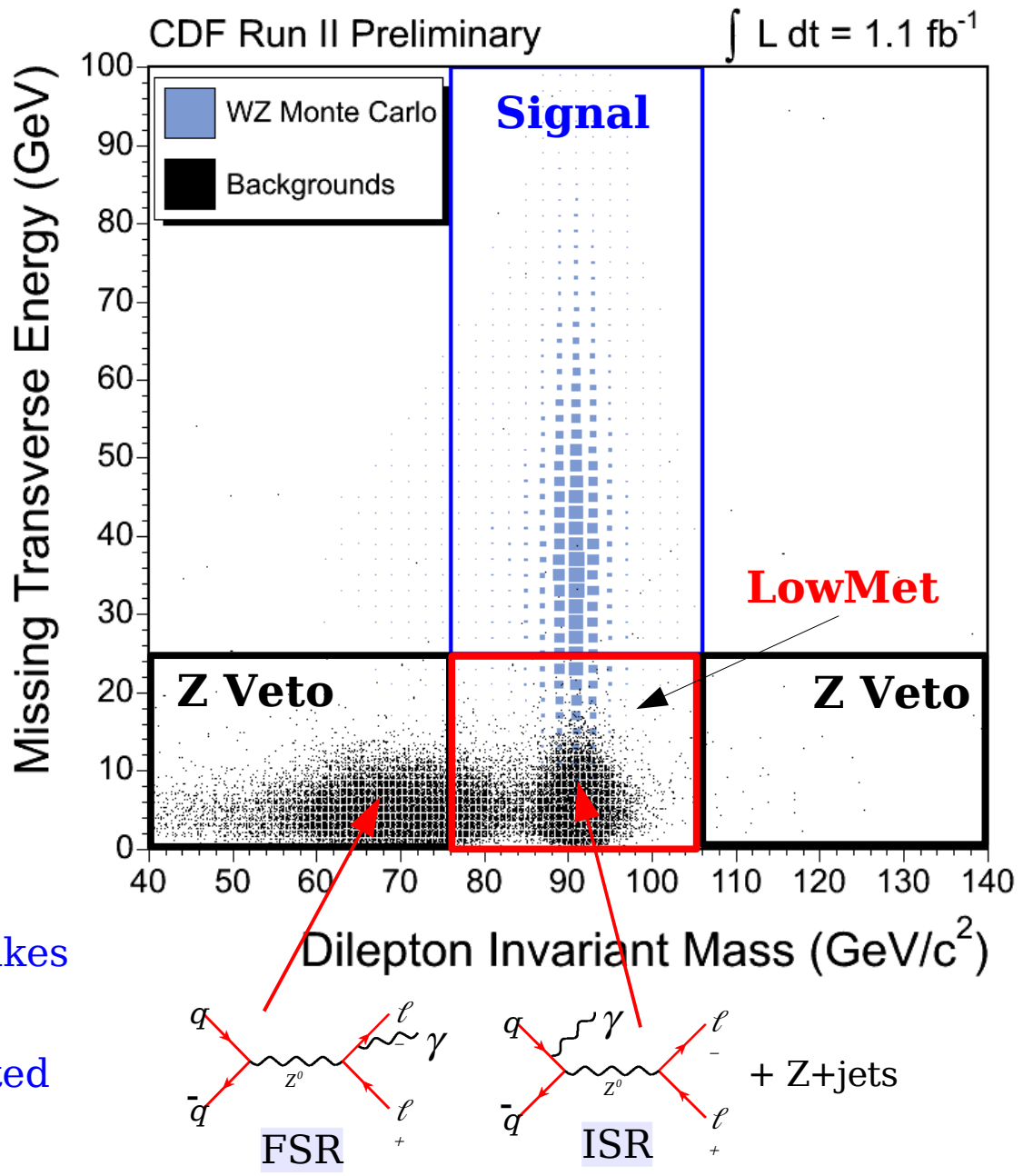
- Z region ($76 < M_{\ell\ell} < 106$)
- Invert $\not{E}_T$ cut

Trilepton Control regions

Tests background modeling

Low MET Region: ← Zγ ISR, Z+jet fakes
- Invert $\not{E}_T$ cut

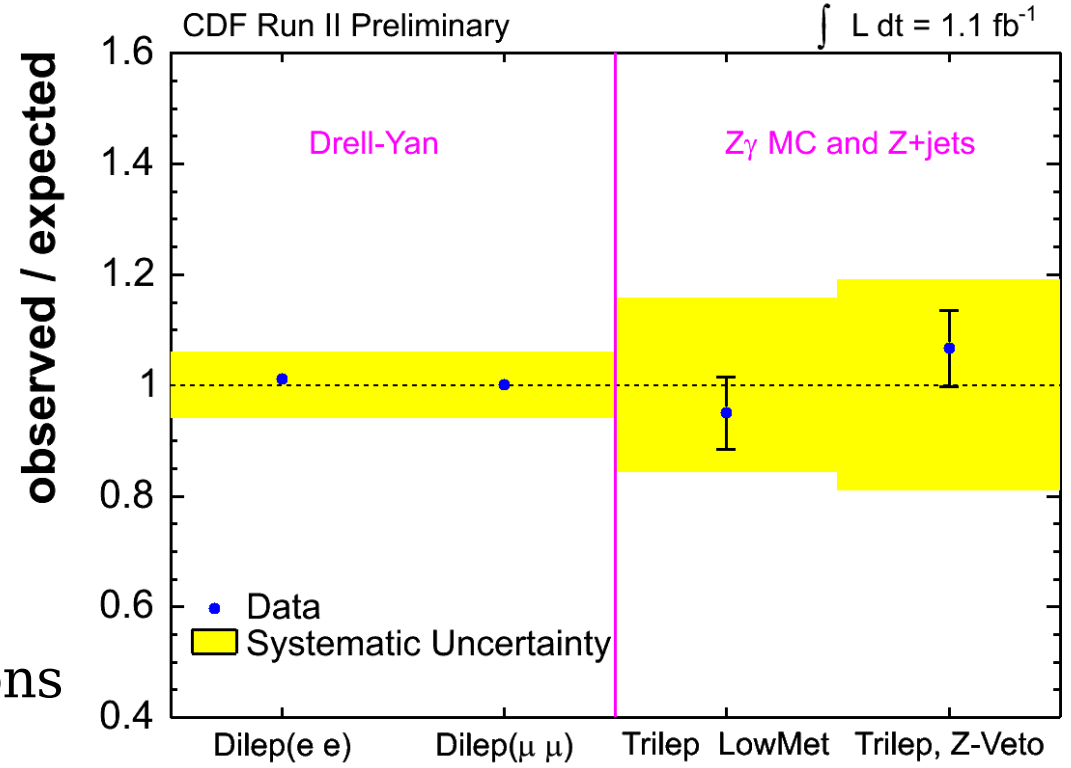
Z Veto Region: ← Zγ FSR dominated
- Invert Z mass cut
- Invert $\not{E}_T$ cut



Region Results

Source	Low MET	Z Veto
ZZ	2.2	0.4
Zγ	157.5	201.6
Z+jets	63.8	23.3
WZ	2.8	0.3
Total Expected	**226.3 ± 35.7**	**225.9 ± 43.2**
Observed	**215**	**241**

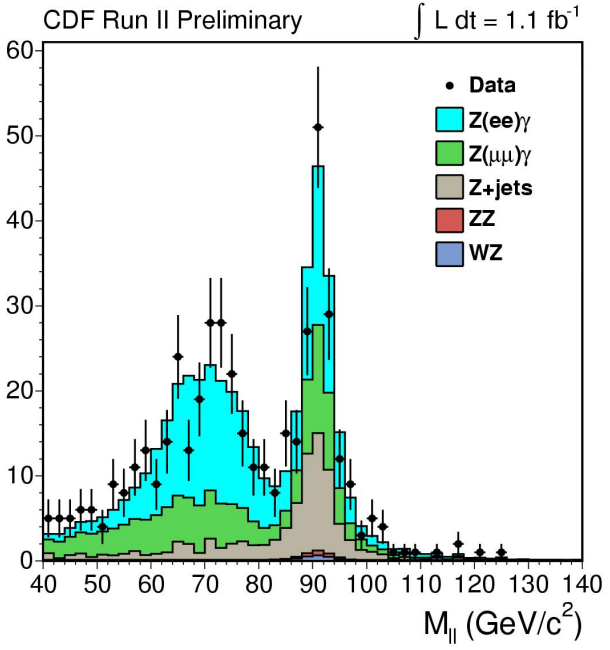
Good agreement in control regions

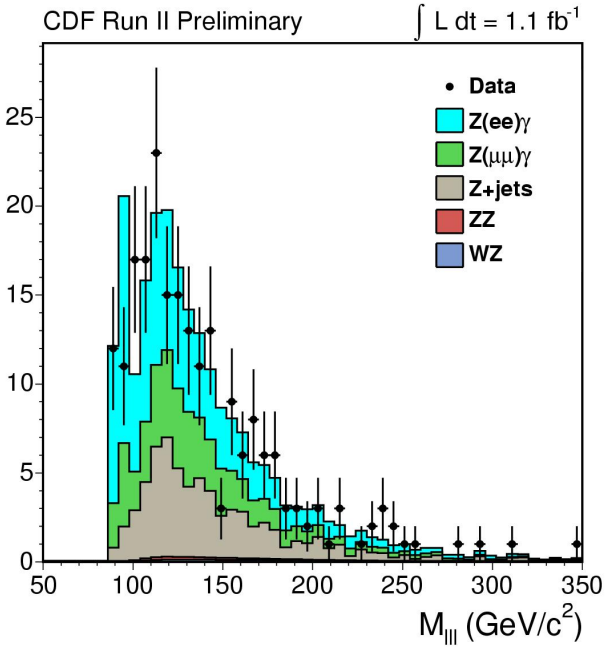


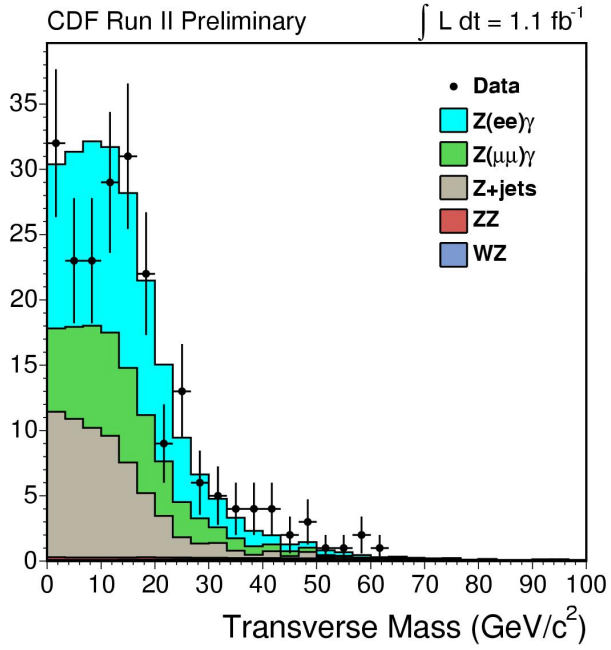
Signal Region

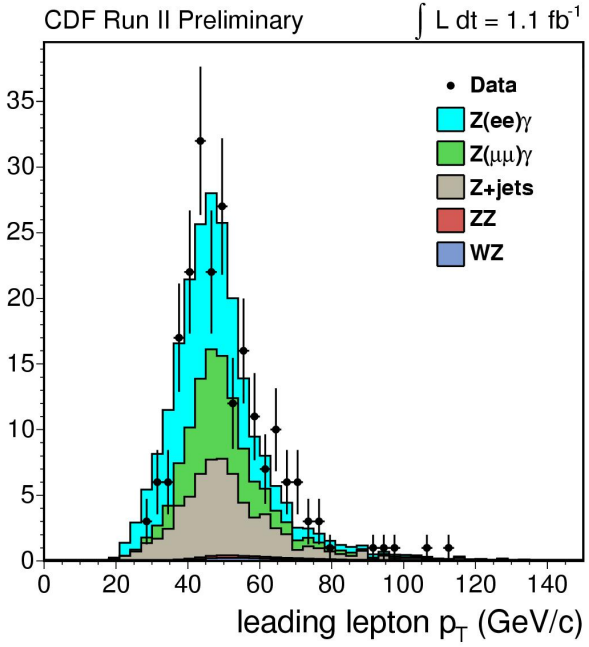
Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	$1.22 \pm 0.27 \pm 0.28 \pm$ -
ZZ	$0.89 \pm 0.01 \pm 0.09 \pm 0.05$
$Z\gamma$	$0.48 \pm 0.06 \pm 0.15 \pm 0.03$
$t\bar{t}$	$0.12 \pm 0.01 \pm 0.01 \pm 0.01$
WZ	$9.79 \pm 0.03 \pm 0.31 \pm 0.59$
Total Background	$2.70 \pm 0.28 \pm 0.33 \pm 0.09$
Total Expected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

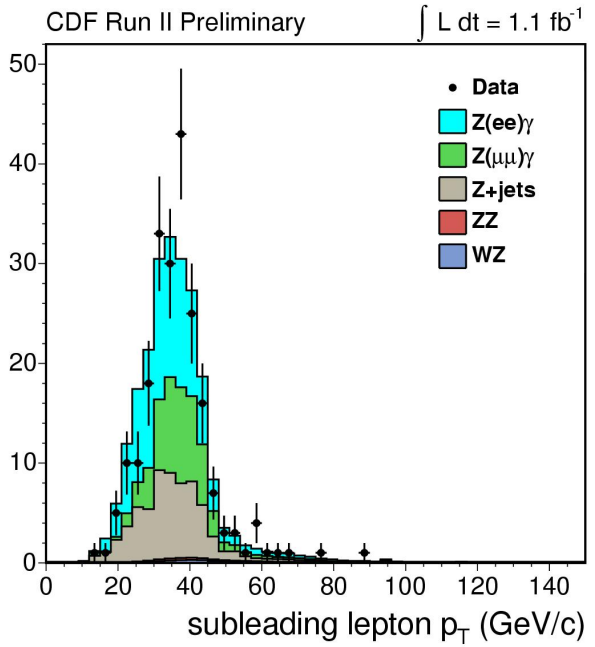
Low MET Region: Kinematics

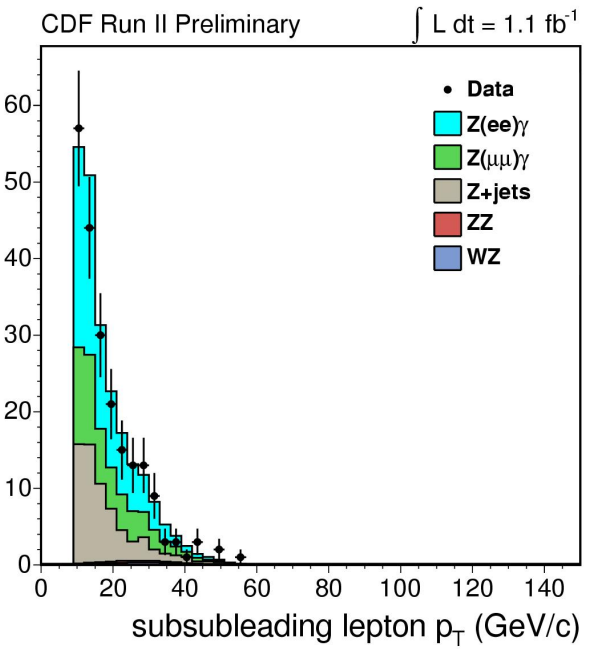




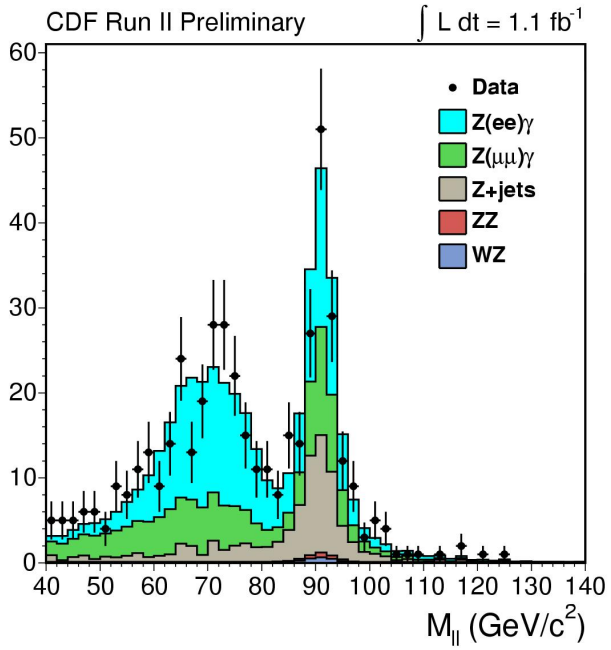


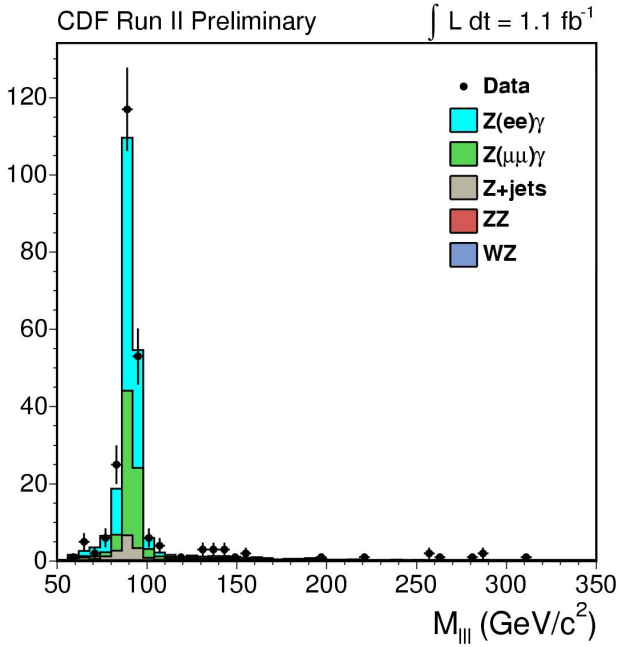


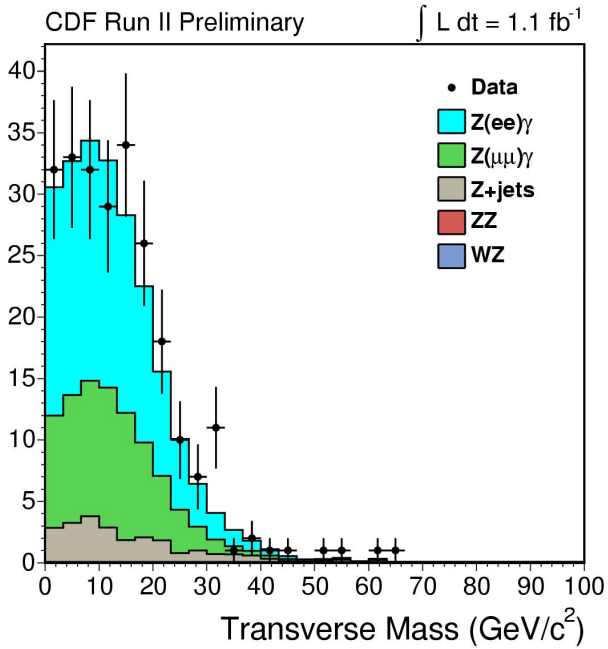


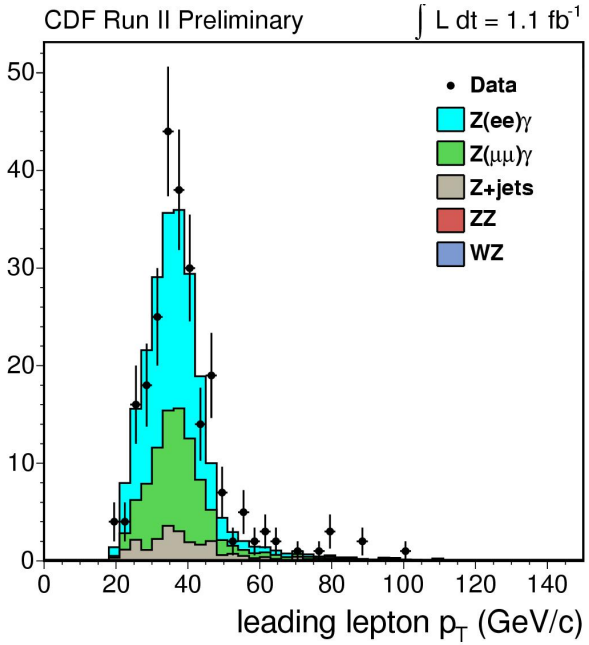


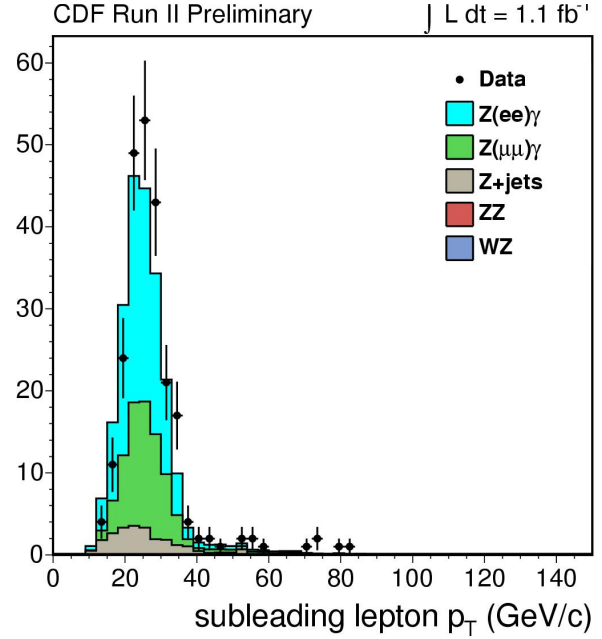
Z Veto Region Kinematics

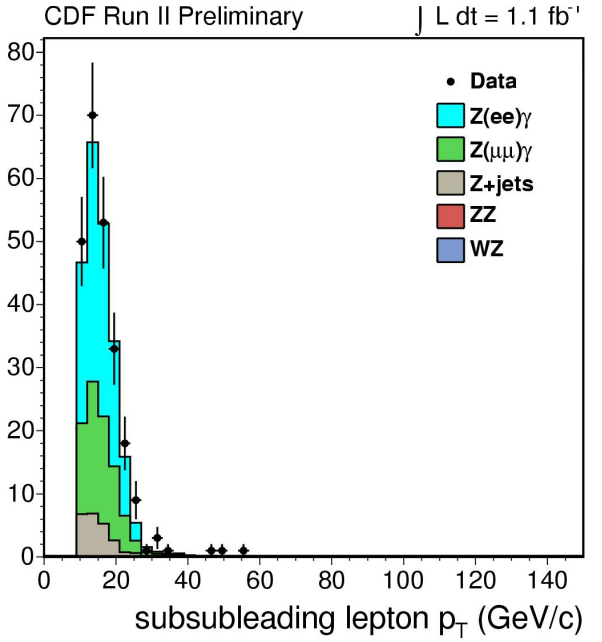






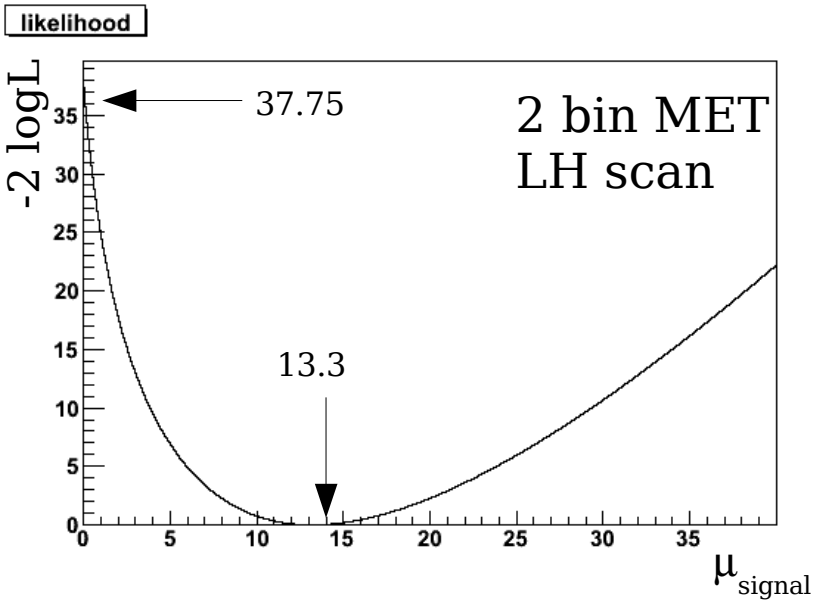






WZ Results

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



Signal Region ($\not\!\!E_T$ > 25 GeV) 1-bin counting:

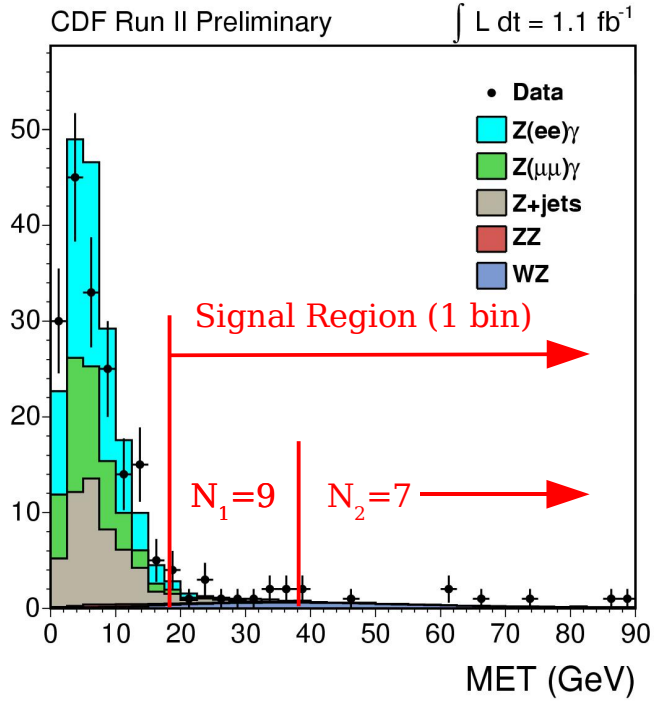
- Prob(background only) < 1.5×10^{-7} (5.1 σ)

Two bins in $\not\!\!E_T$ (chosen a priori using independent samples

- N_{obs} (25 < $\not\!\!E_T$ < 45 GeV) = 9
- N_{obs} (45 < $\not\!\!E_T$ < ∞ GeV) = 7

Prob(background only) < 2×10^{-9} (5.9 σ)

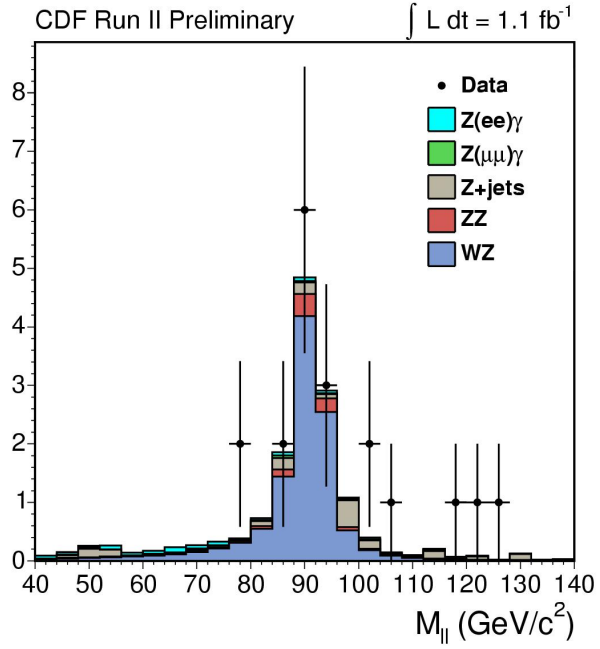
⇒ First observation of WZ production!

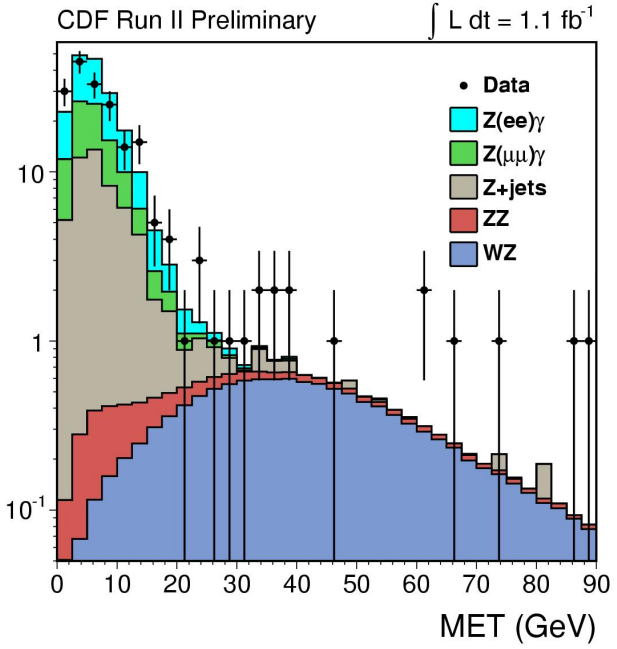


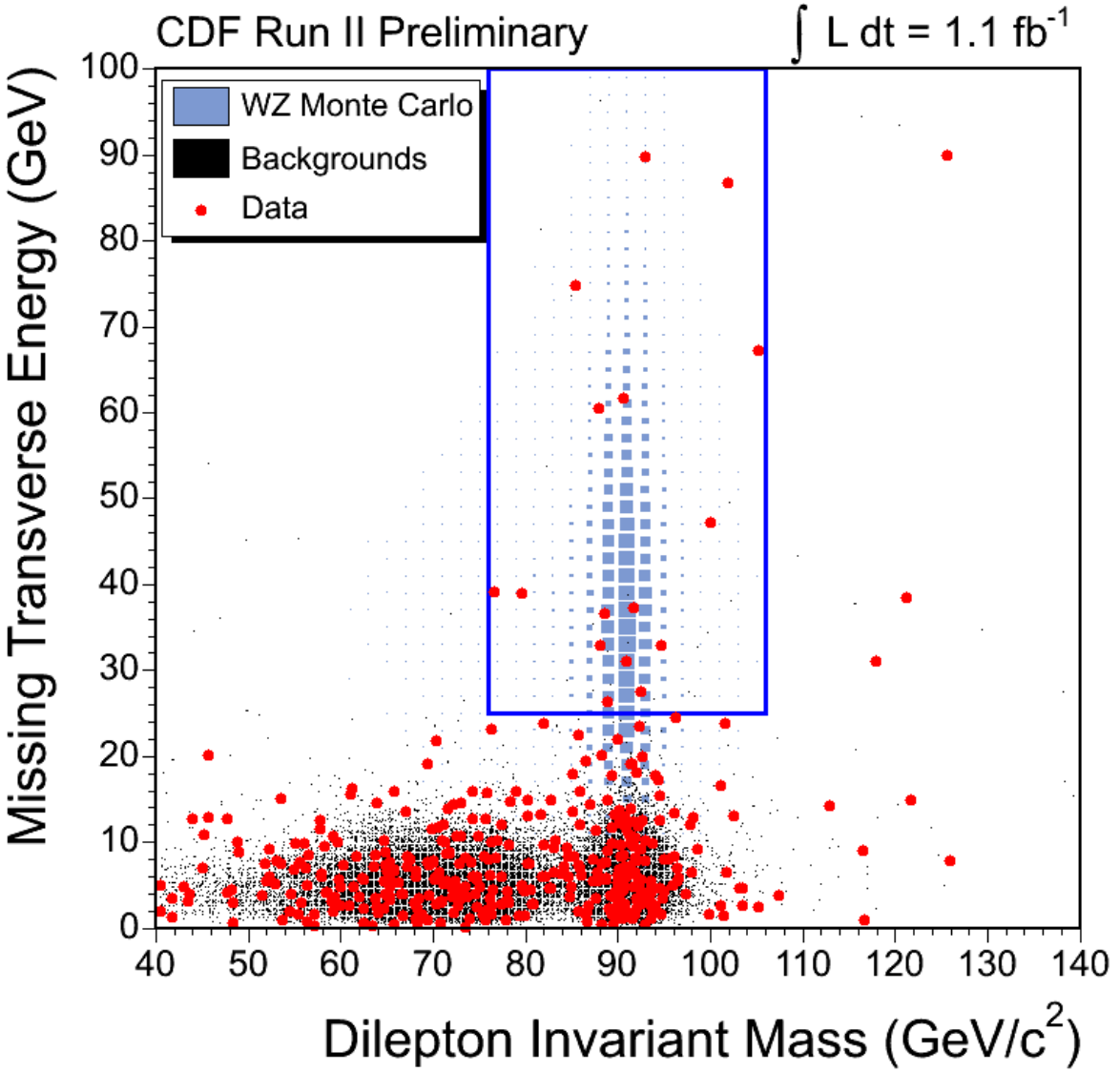
We also note that our 2-bin result is ordinary for the sum of Standard Model WZ and background.

- 49% of pseudo-experiments have a joint 2-bin probability smaller than our data

WZ Results



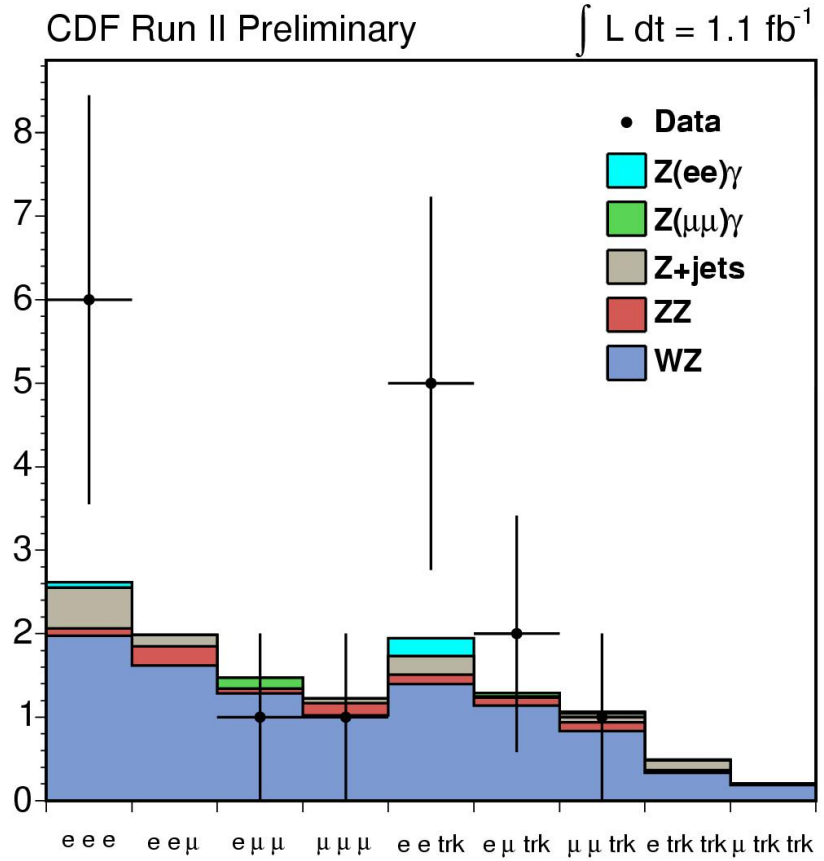


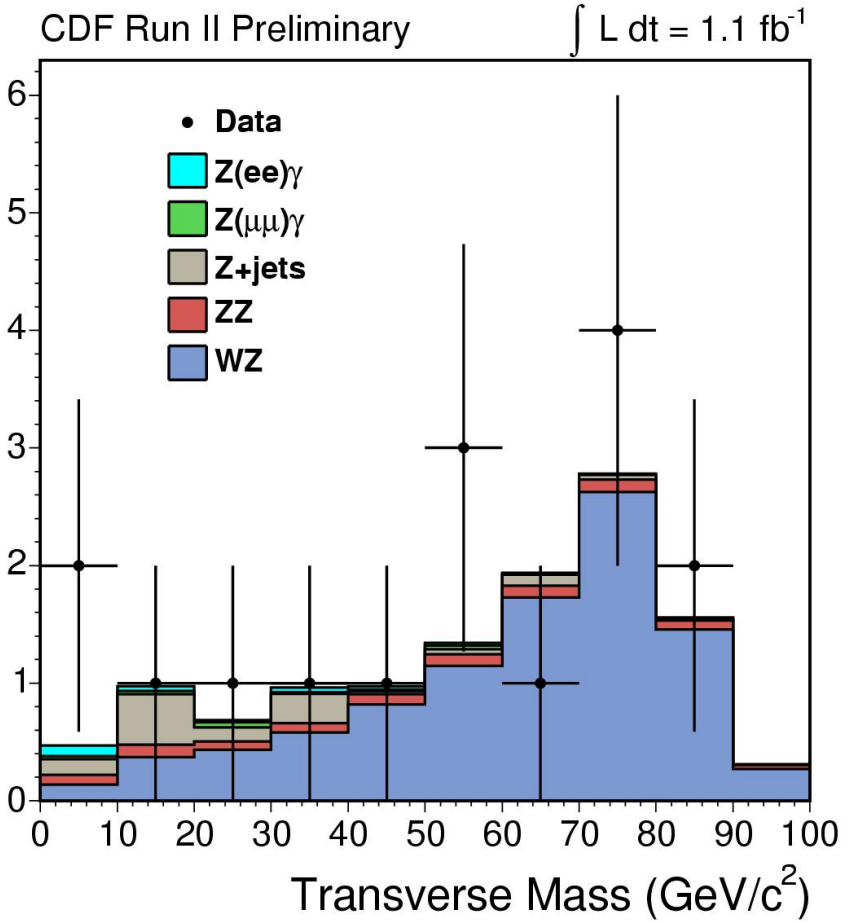


$\sigma(WZ) = 5.0^{+1.8}_{-1.6}$ (stat.+syst.) pb

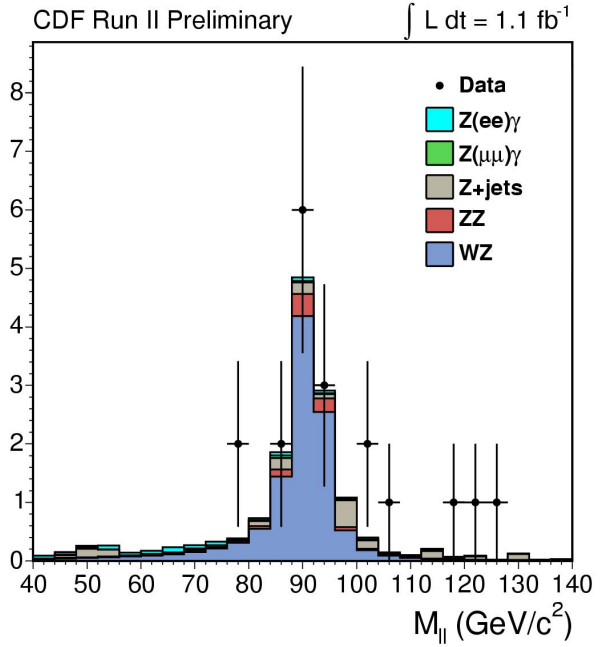
consistent with NLO
σ(WZ) = 3.7±0.3 pb

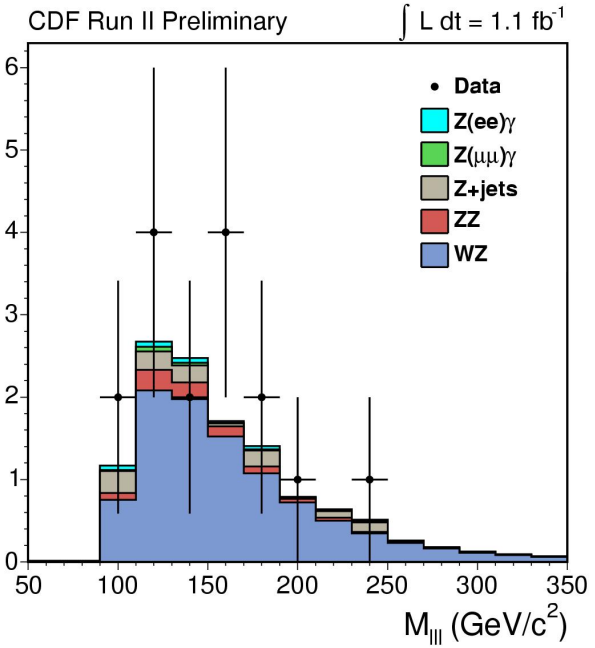
WZ Signal Region Kinematics

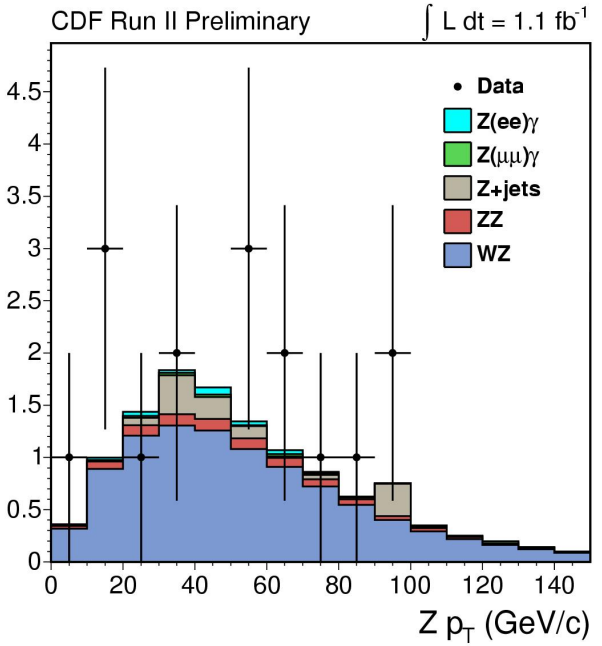


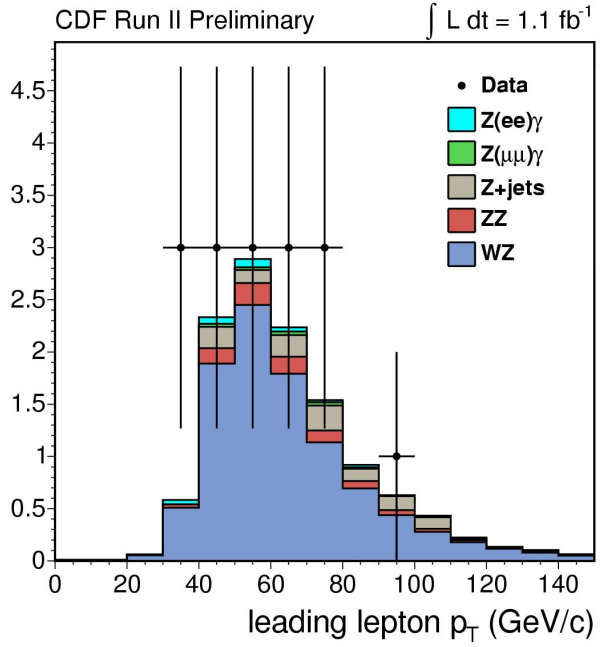


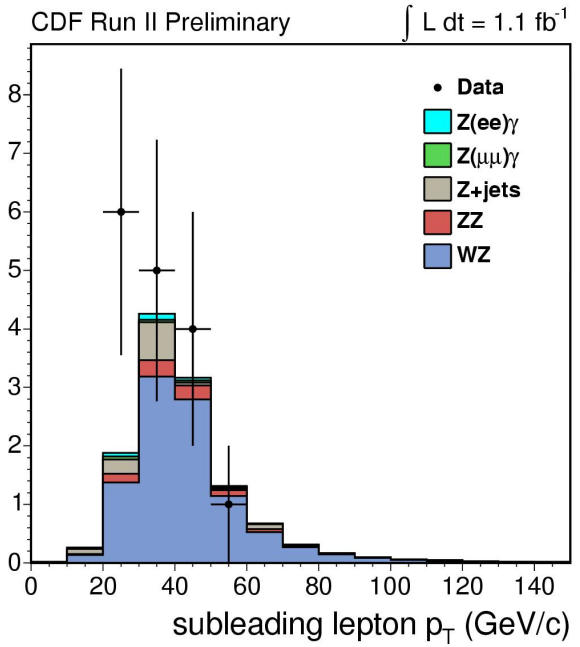
WZ Signal Region Kinematics

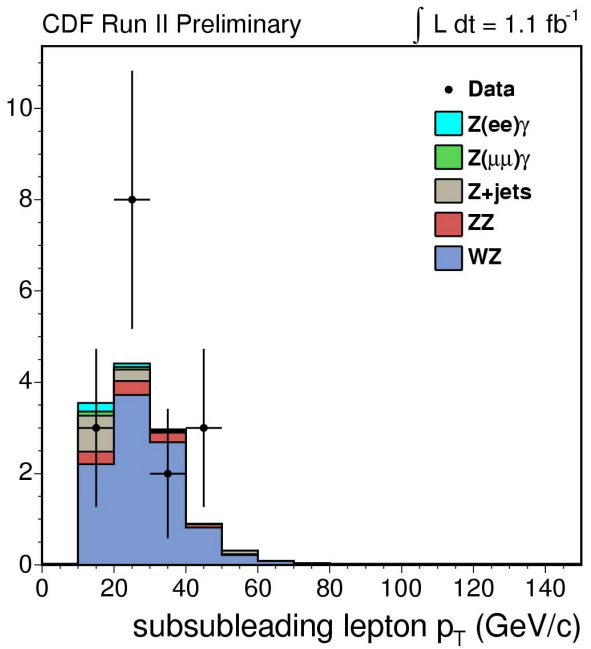




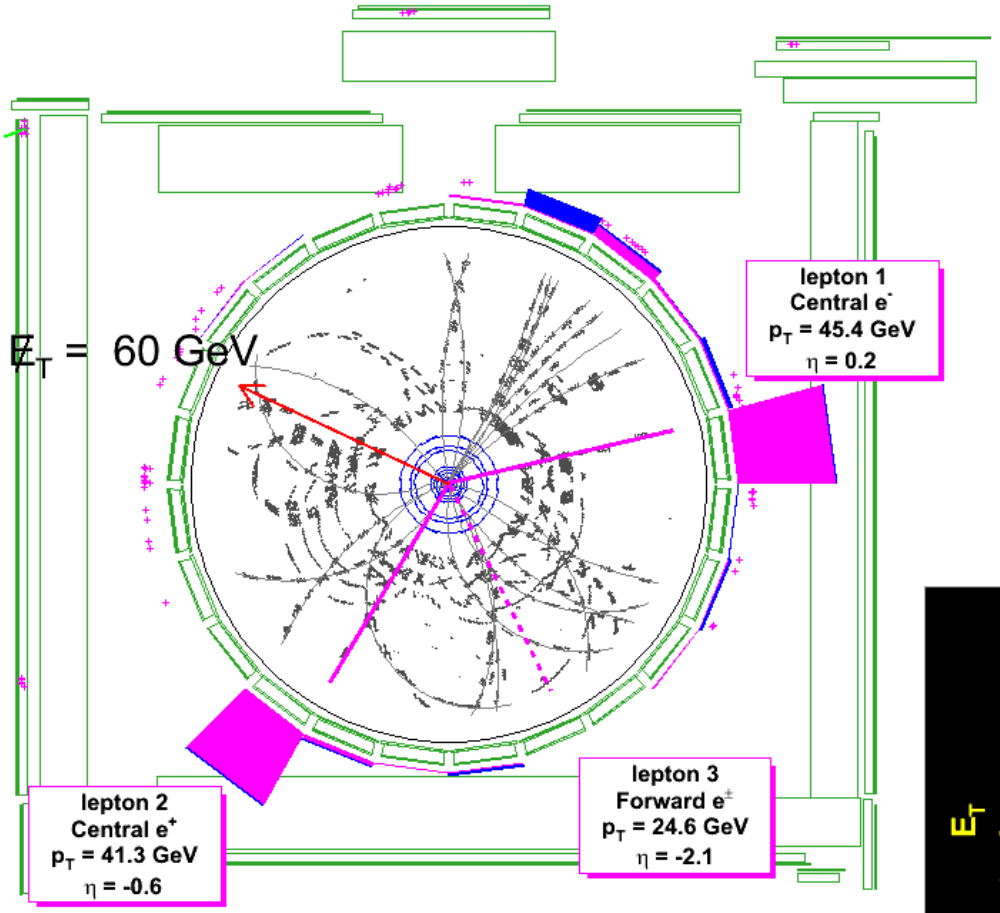


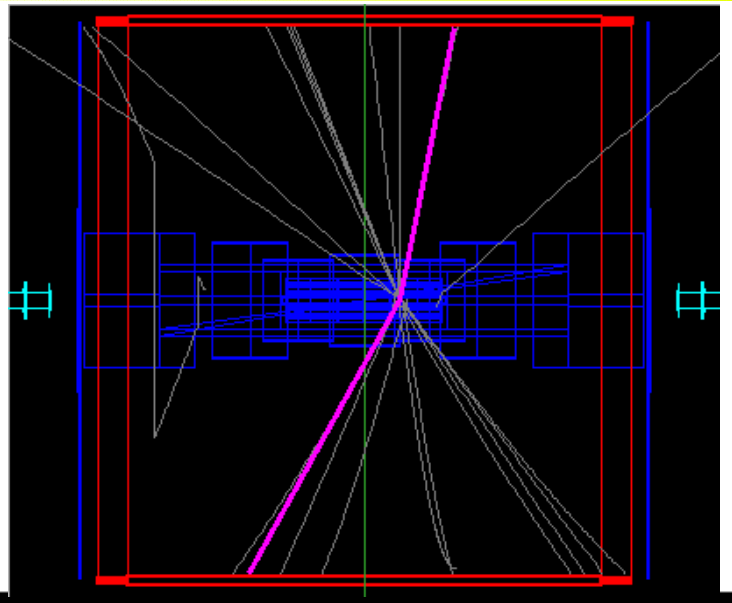


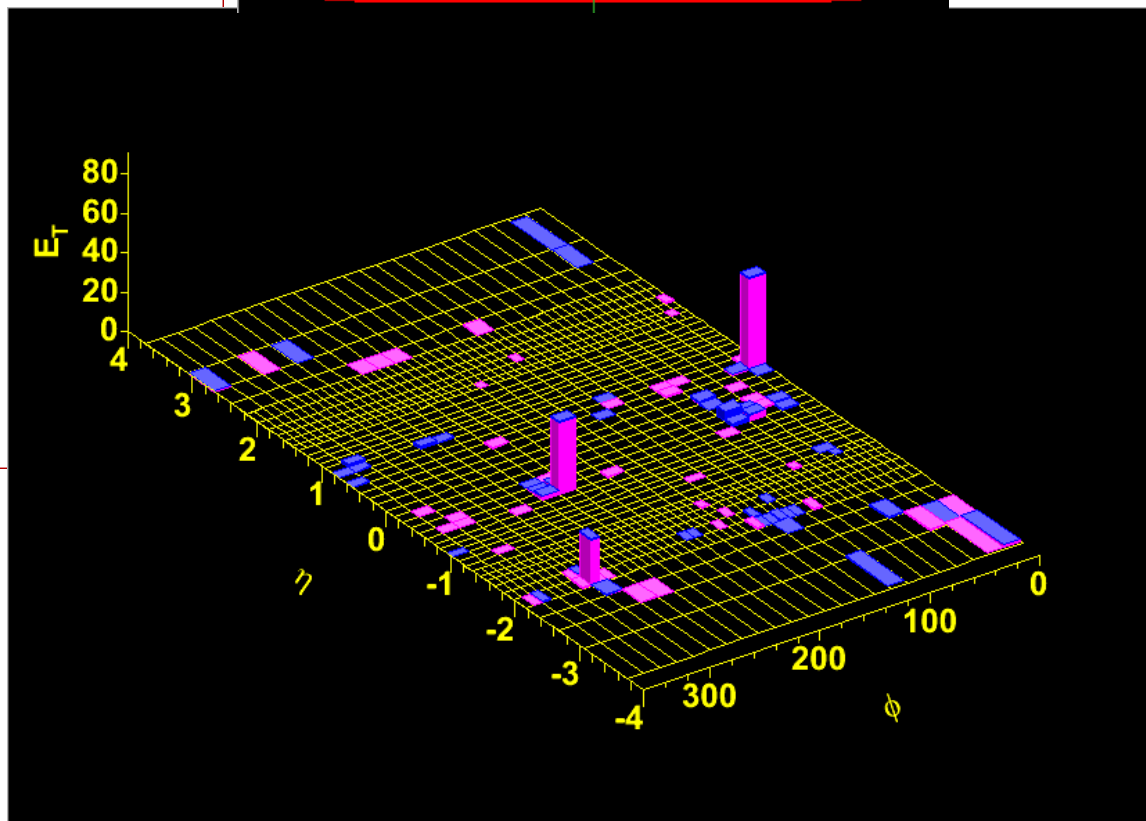




$W^{\pm}Z^{0} \rightarrow e^{\pm}\overset{(-)}{\nu}_{e}e^{+}e^{-}$ Candidate





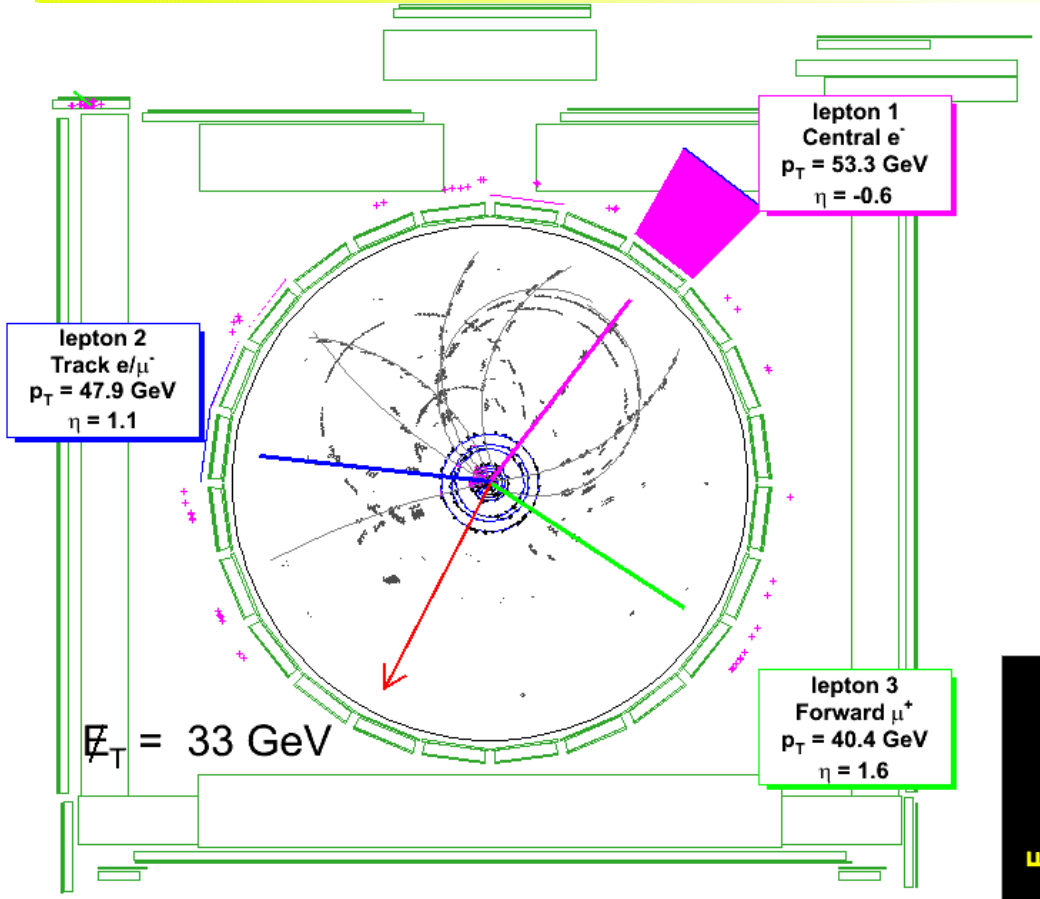


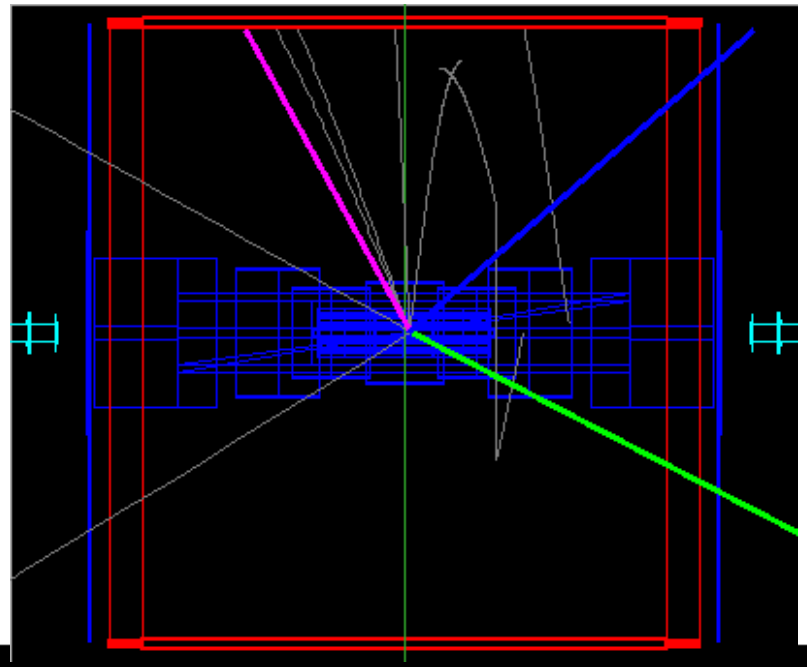
Run=154799 Event=1795709

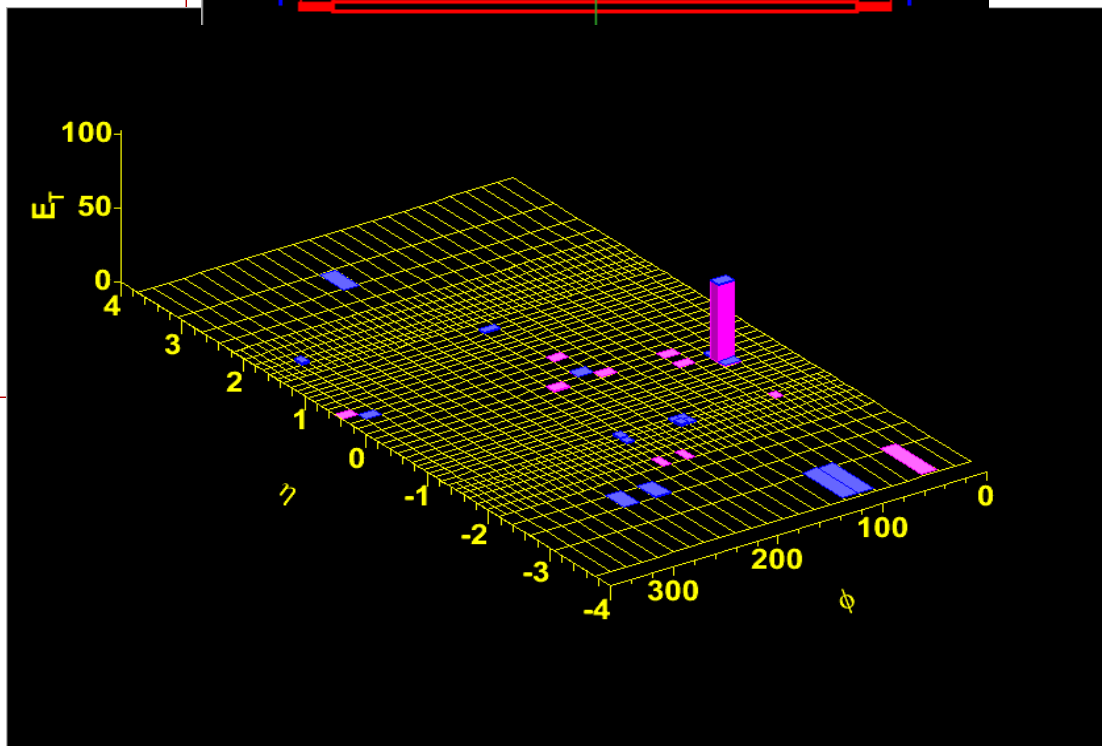
m_{12}=87.91 GeV $\quad |\not\!\!E_T|$=60.5 GeV
m_{13}=104.37 GeV $\quad \Delta\phi(\not\!\!E_T, \text{lepton, jet})$=1.5
m_{23}=59.62 GeV

Type	p_t	η	ϕ
Central e	45.4	0.2	0.2
Central e	41.3	-0.6	-2.1
Forward e	24.6	-2.1	-1.1

$W^{-}Z^{0} \rightarrow e^{-}\bar{\nu}_{e}\mu^{+}\mu^{-}$ Candidate







Run=167634 Event=627292

m_{12}=131.15 GeV $|\not\!\!E_T|$=32.8 GeV
m_{13}=136.36 GeV $\Delta\phi(\not\!\!E_T, \text{lepton, jet})$=1.2
m_{23}=88.09 GeV

Type	p_t	η	ϕ
Central e	53.3	-0.6	0.9
Track e/μ	47.9	1.1	3.0
Forward μ	40.4	1.6	-0.6

$ZZ \to \ell^+\ell^-\ell^+\ell^-$ Search Analysis

Background estimation:

Expect backgrounds from Z+jets, Zγγ

- Zγγ: Madgraph + Pythia + GEANT
- Z+jets from data

$Z^0Z^0 \to \ell^+\ell^-\ell^+\ell^-$ Selection:

- Triggers:
  Central $e^{\pm}$, Central $\mu^{\pm}$ (CMUP,CMX)
- 4 leptons (e,μ) with E_T > 20,10,10,10 GeV
- Z mass regions:
  ≥1 opp-sign, same-flavor lepton pair in (76, 106)
  ≥1 additional opposite-sign, same-flavor pair in (40, 140)

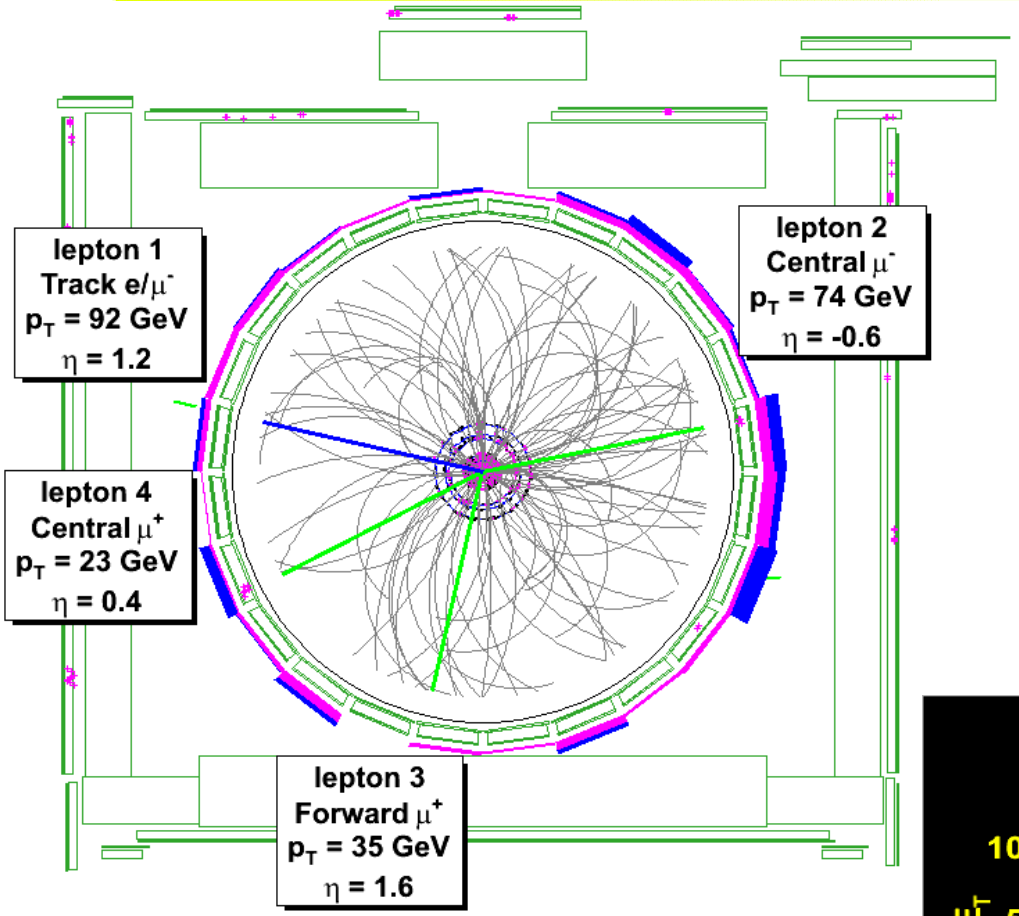
Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	$0.007 \pm 0.007 \pm 0.004 \pm$ -
$Z\gamma\gamma$	$0.002 \pm 0.001 \pm 0.000 \pm 0.000$
ZZ	$1.884 \pm 0.015 \pm 0.061 \pm 0.113$
Total Background	$0.009 \pm 0.007 \pm 0.004 \pm 0.000$
Total Expected	$1.893 \pm 0.017 \pm 0.062 \pm 0.113$
Observed	**1**

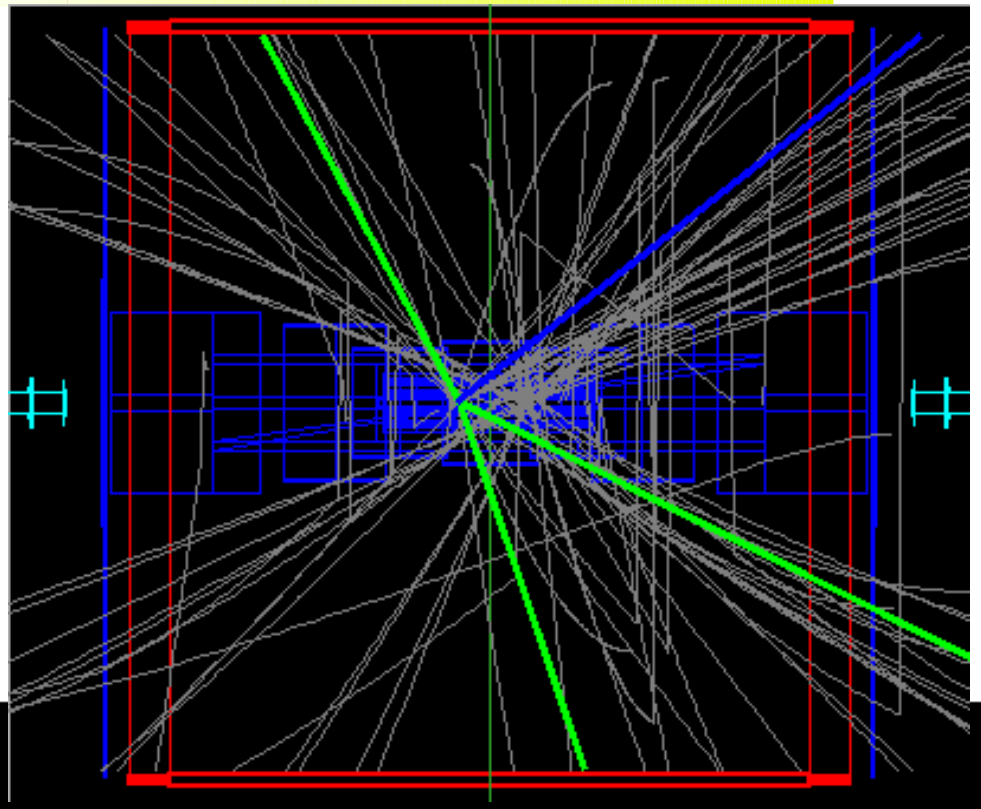
We can exclude the background-only hypothesis at 2.6 σ

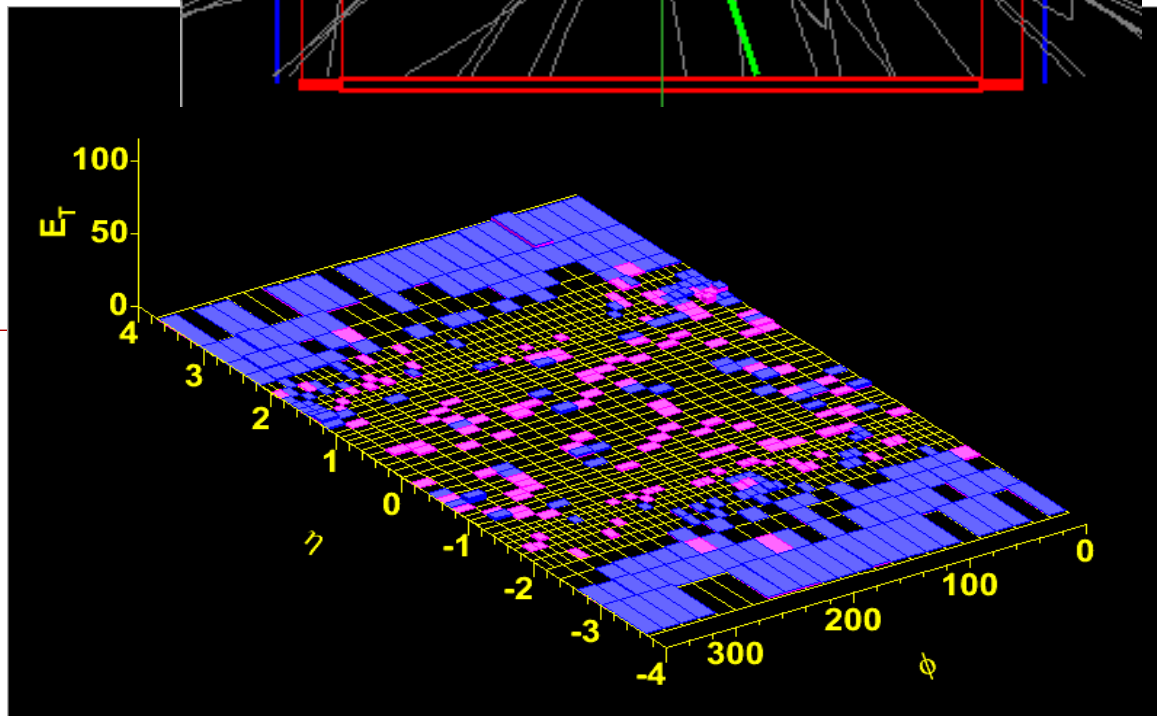
We determine: $\sigma(ZZ) < 3.8$ pb (95% C.L.)

consistent with NLO
σ(ZZ) = 1.4±0.1 pb

$Z^0Z^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$ Candidate







Run=211311 Event=233113

m_{ll1}=90.92 GeV $\quad |\not\!\!E_T|$=8.7 GeV
m_{ll2}=83.03 GeV $\quad N_{jets} = 0$
M_{lll}=312.4 GeV/c^2

Type	p_t	η	ϕ
Track e/μ	91.5	1.2	2.9
Central μ	74.1	-0.6	0.2
Forward μ	34.5	1.6	-1.8
Central μ	22.5	0.4	-2.7

Summary

Using $\int L\, dt = 1.1\ fb^{-1}$ of data, we searched for WZ and ZZ production.

We observe 16 WZ $\rightarrow$ 3 leptons + E_T candidates with an expected background of $2.70 \pm 0.28\ (stat.) \pm 0.34\ (syst.)$

$\Rightarrow$ First observation (5.9σ) of WZ production!

Our measured cross section is:

$$\sigma(WZ) = 5.0^{+1.8}_{-1.6}\ (stat.+syst.)\ pb$$

We observe 1 ZZ $\rightarrow \mu^+\mu^-\mu^+\mu^-$ candidate with an expected background of

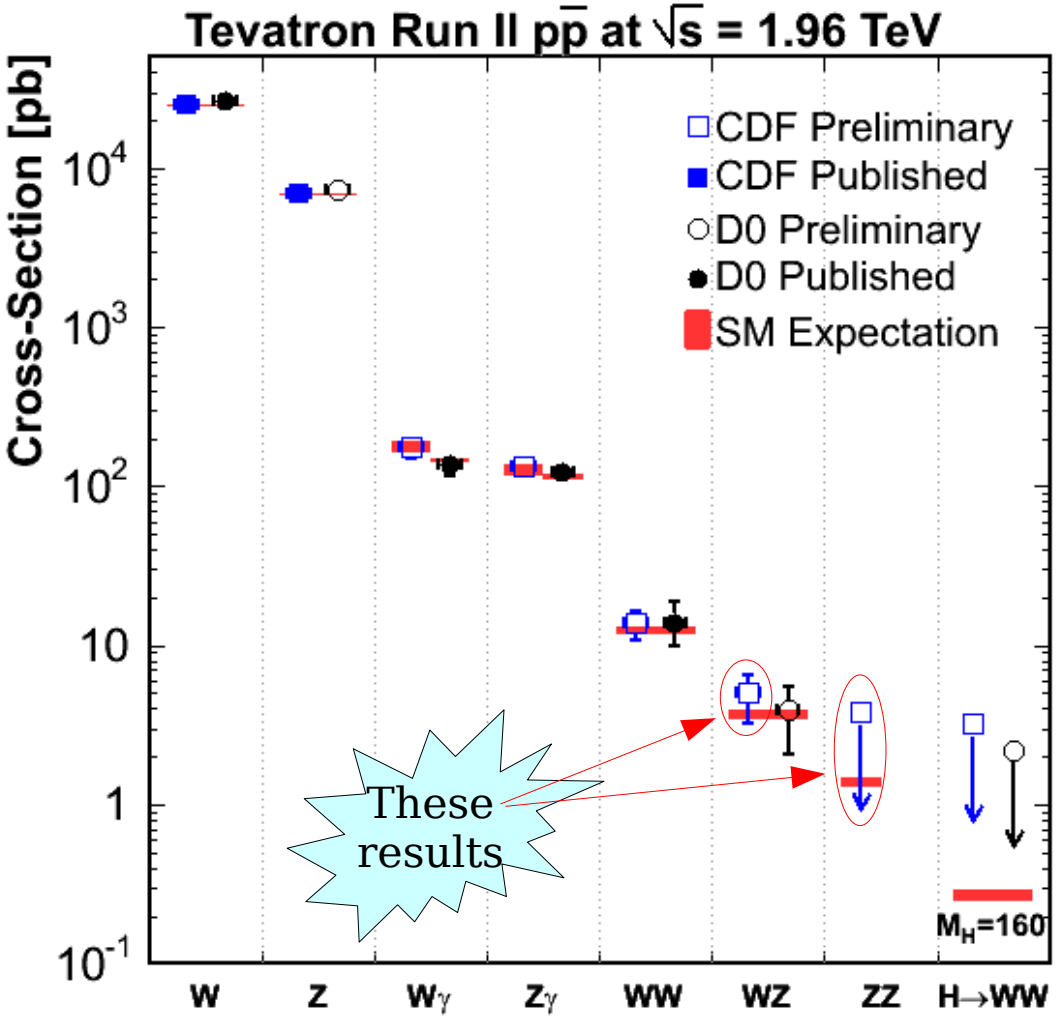
$0.009 \pm 0.007\ (stat.) \pm 0.004\ (syst.)$

and ZZ signal of

$1.884 \pm 0.015\ (stat.) \pm 0.128\ (syst.)$

We set the following limit:

$$\sigma(ZZ) < 3.8\ pb\ (95\%\ C.L.)$$



Extras

Previous $W^{\pm}Z^0 \to \ell^{\pm}\ell^{+}\ell^{-}\nu$ Search

Using $\int L\, dt = 0.8\ fb^{-1}$

$W^{\pm}Z^0 \to \ell^{\pm}\ell^{+}\ell^{-}\nu$ selection:

- 3 leptons (e,μ) with Pt > 20,10,10 GeV/c
- Z^0 region: $76 < M(\ell^{+}\ell^{-}) < 106$ GeV/c^2
- $\not\!\!E_T > 25$ GeV

Observe 2 events (eee) with an expected background of 0.9±0.2 and signal of 3.7±0.3

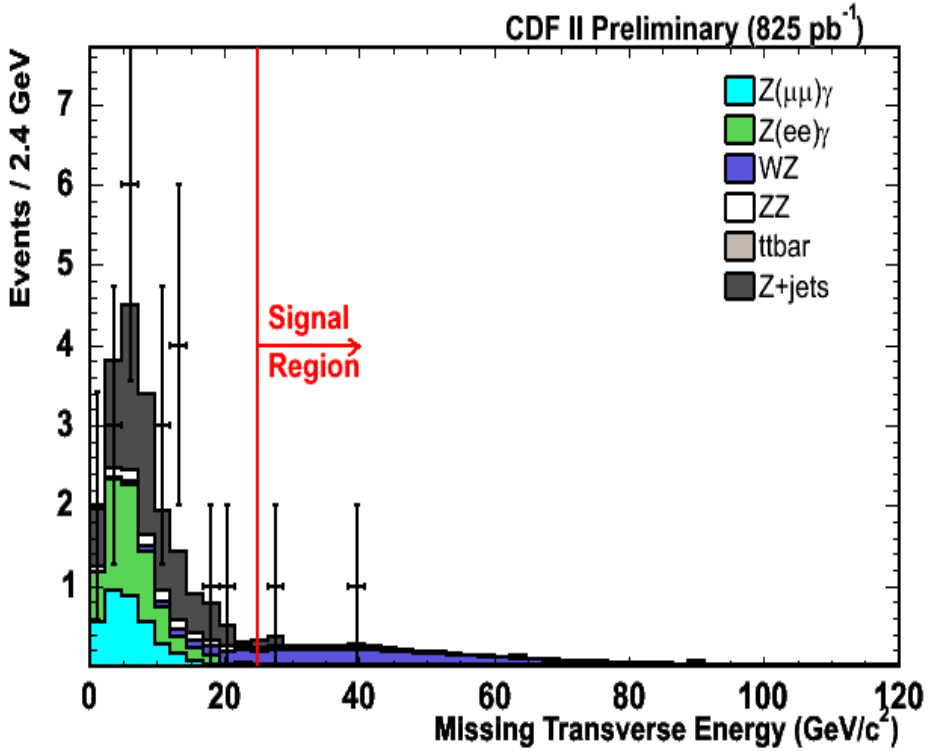
$\sigma(WZ) < 6.34$ pb (95% C.L.)

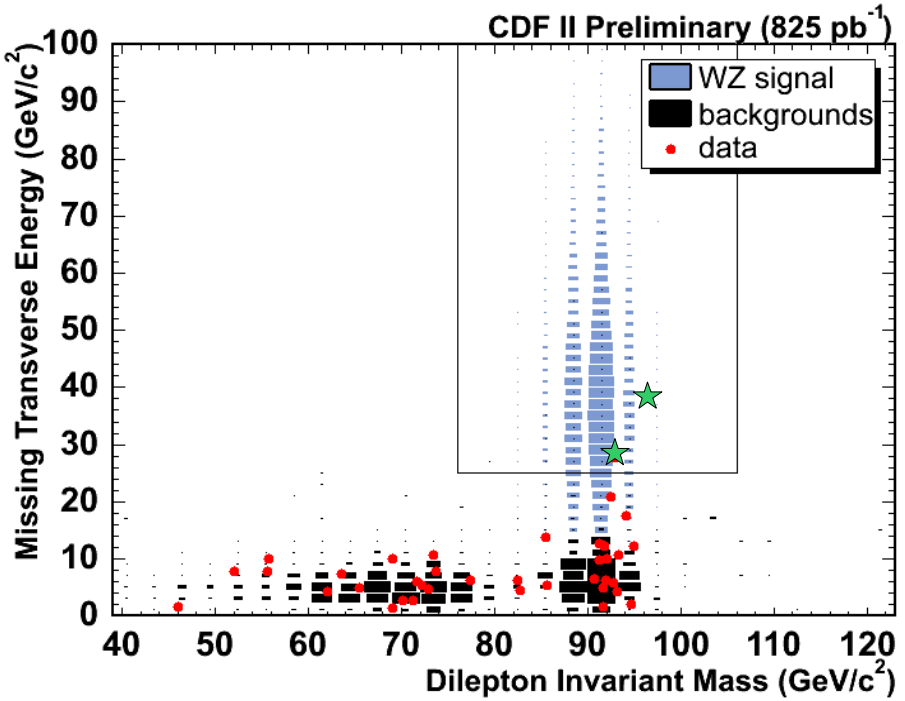
Signal:

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.)





WZ Analysis Systematics

Variation	ZZ	$Z\gamma$	$t\bar{t}$	WZ
Expected Yield	0.9	0.5	0.1	9.8
Lepton Id Efficiency	$\pm$ 2.0%	$\pm$ 1.9%	$\pm$ 1.2%	$\pm$ 1.9%
Trigger Efficiency	$\pm$ 0.6%	$\pm$ 0.9%	$\pm$ 0.4%	$\pm$ 0.6%
$\not\!\!E_T$ Modeling	$\pm$ 1.0%	$\pm$ 25.0%	$\pm$ 1.0%	$\pm$ 1.0%
Energy Scale	$\pm$ 1.0%	$\pm$ 1.0%	-	$\pm$ 1.0%
PDF Uncertainty	$\pm$ 2.0%	$\pm$ 2.0%	$\pm$ 2.0%	$\pm$ 2.0%
Cross-Section	$\pm$ 10.0%	$\pm$ 20.0%*	$\pm$ 10.0%	-
Total	$\pm$ 10.5%	$\pm$ 32.2%	$\pm$ 10.3%	$\pm$ 3.2%

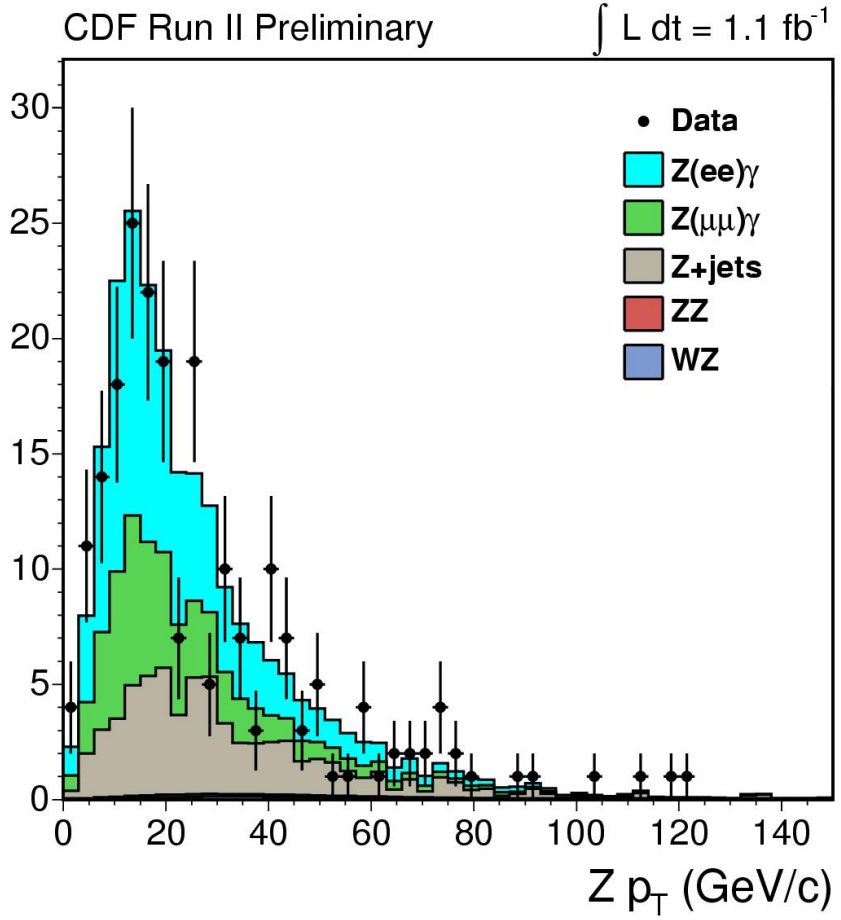
* includes conversion and material description systematics.

ZZ Analysis Systematics

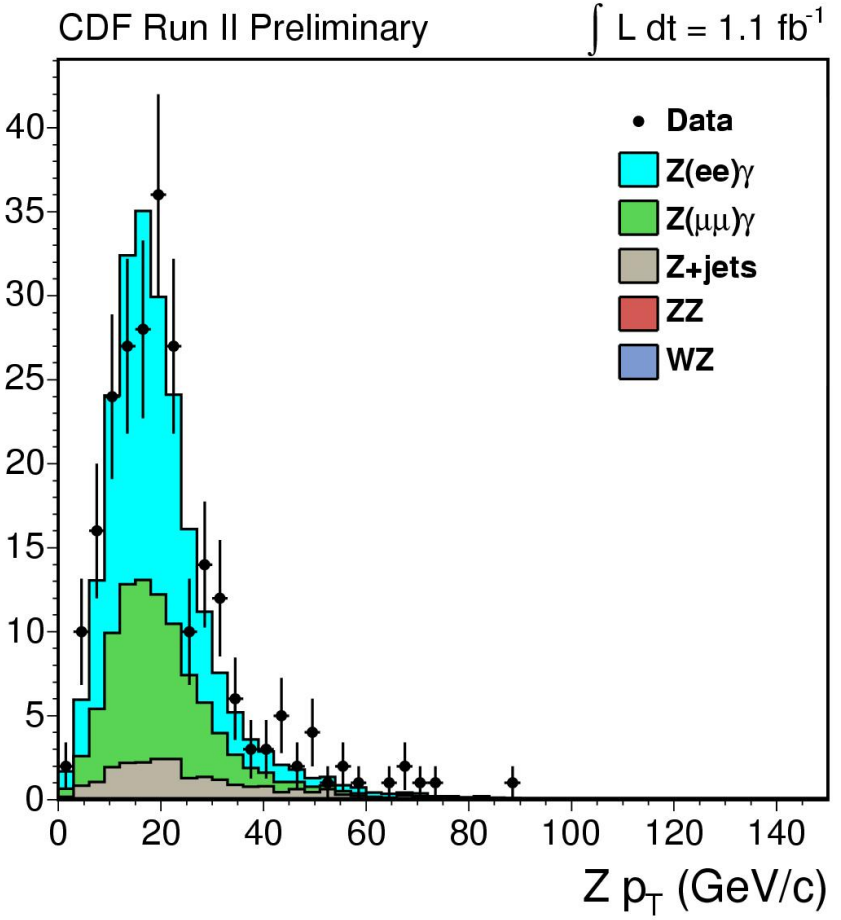
Source	Uncertainty
Expected Yield	1.88
Lepton Id Efficiency	$\pm$ 2.2%
Trigger Efficiency	$\pm$ 0.8%
$\not\!\!E_T$ Modeling	$\pm$ 1.0%
Energy Scale	$\pm$ 1.0%
PDF Uncertainty	$\pm$ 2.0%
Total	$\pm$ 3.4%

Control Regions: Z Pt

Low MET

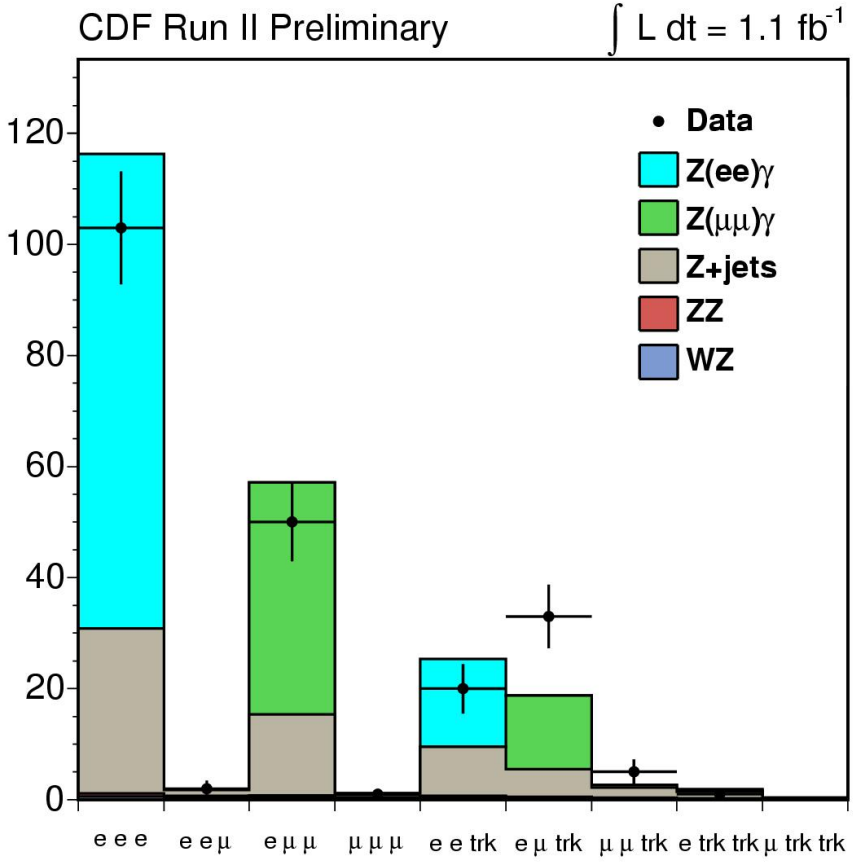


Z Veto

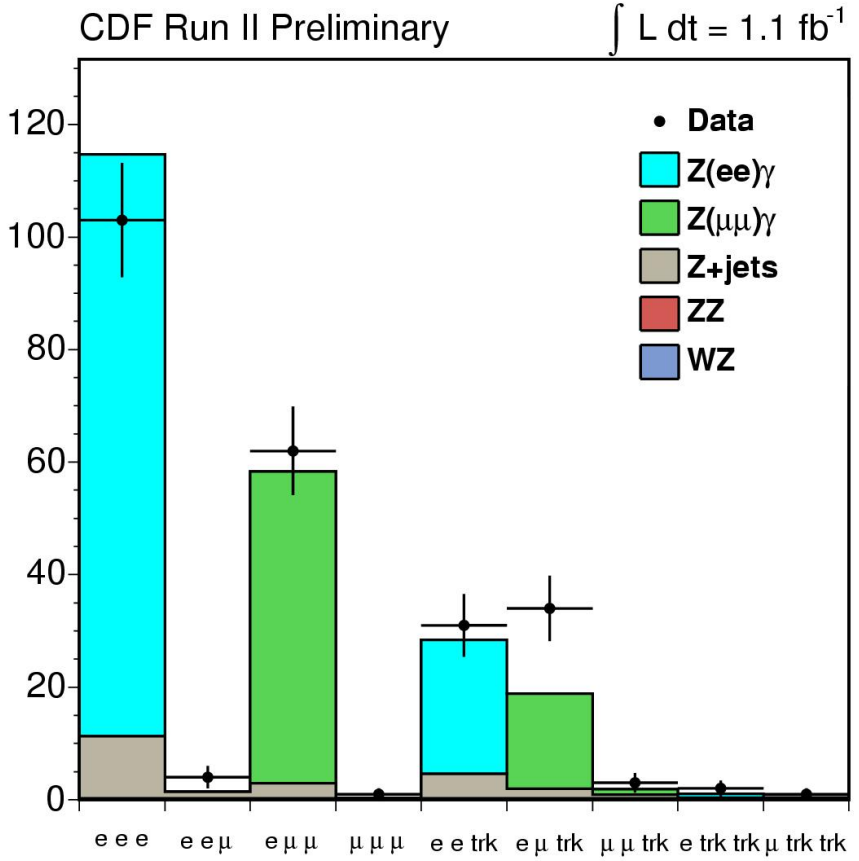


Control Regions: Flavors

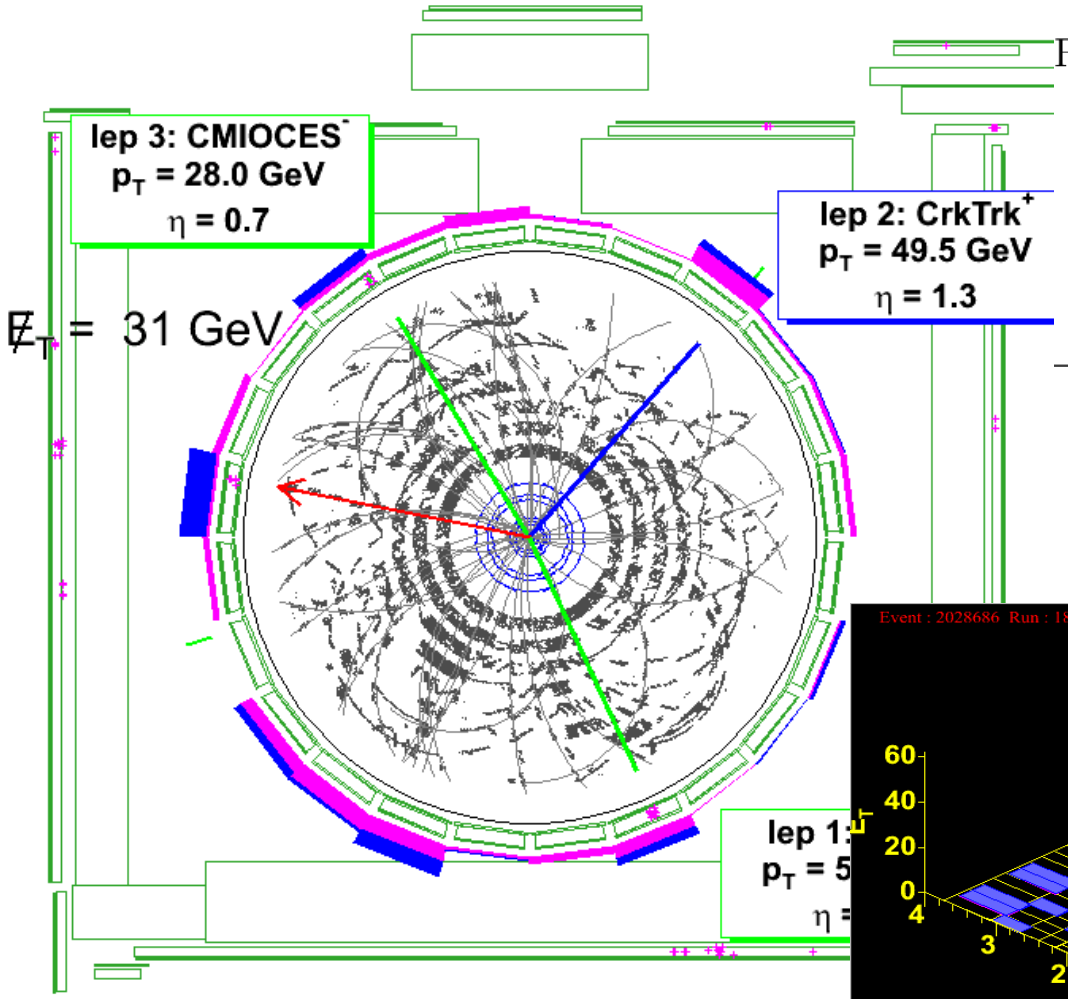
Low MET



Z Veto



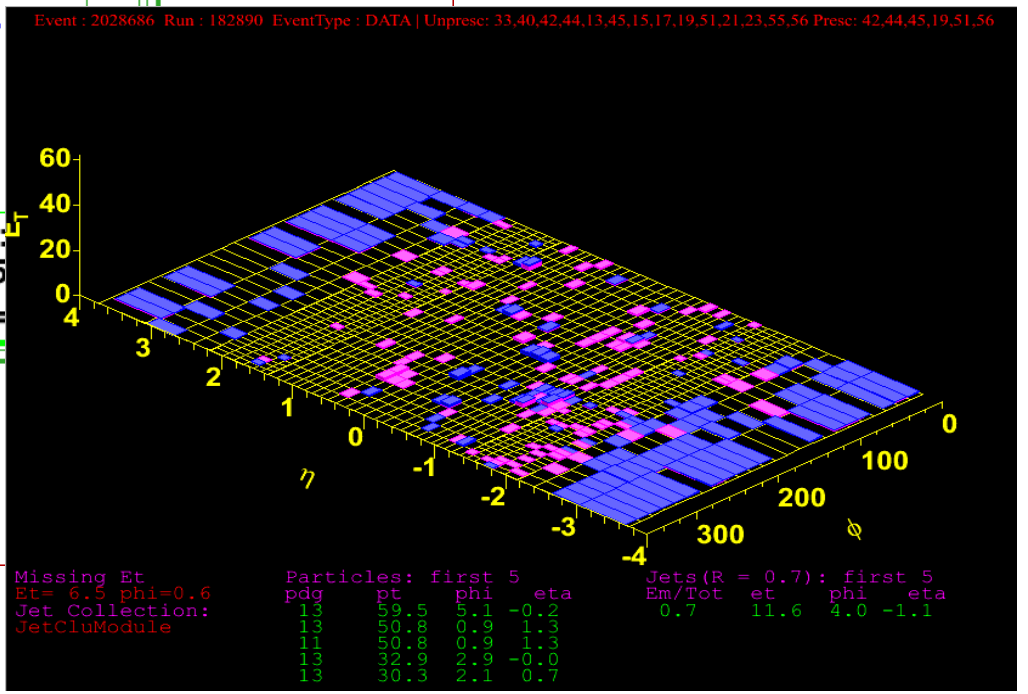
MlepTrk vetoed event



Run=182890 Event=2028686

m_{12}=131.40 GeV $|\not\!\!E_T|$=31.3 GeV
m_{13}=90.61 GeV $\Delta\phi(\not\!\!E_T, \text{lepton, jet})$=0.8
m_{23}=49.63 GeV

Type	p_t	η	ϕ
CMUP	59.9	-0.2	-1.1
CrkTrk	49.5	1.3	0.9
CMIOCES	28.0	0.7	2.1

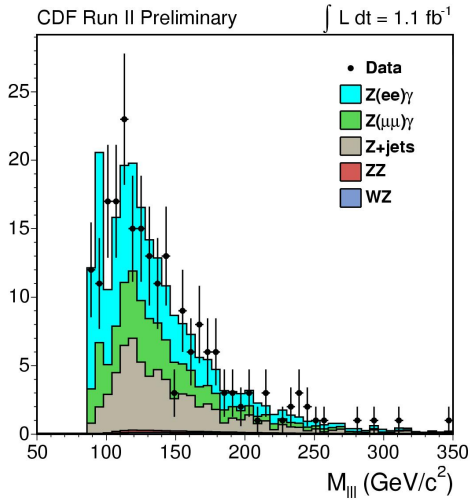


Veto track right behind MET vector
Iso = 0.15
Track pt ~ MET so we'd get small METcorr
Probably ZZ → 4 μ event that we (rightly) vetoed

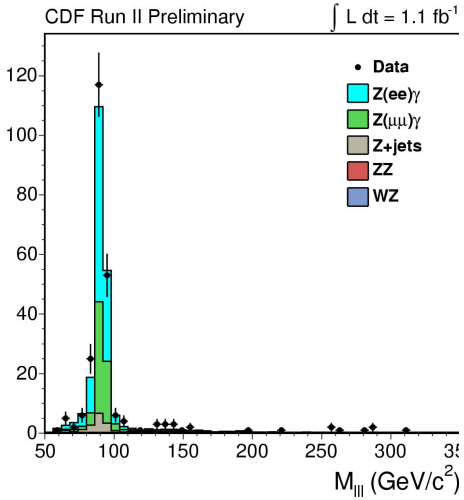
WZ Control / Signal Regions

Trilepton Mass

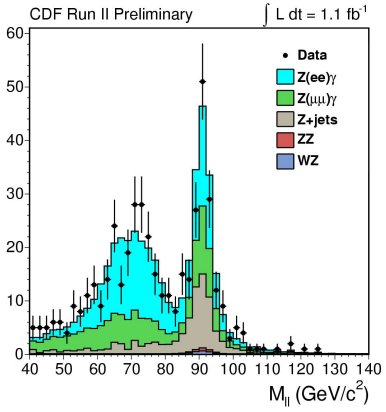
LowMet (ISR)



Z Veto (FSR)



Dilepton Mass



3-body vs. 2-body m