WZ and Wγ Diboson Physics From DØ

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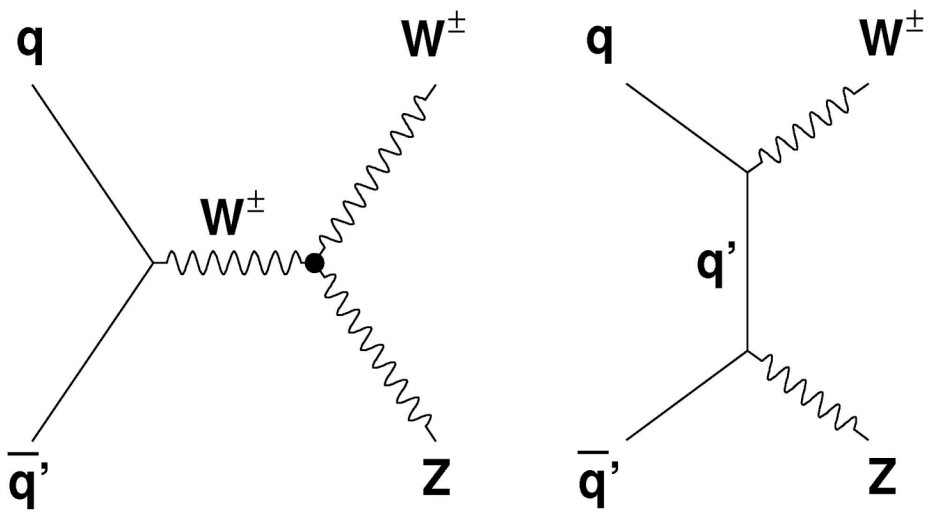
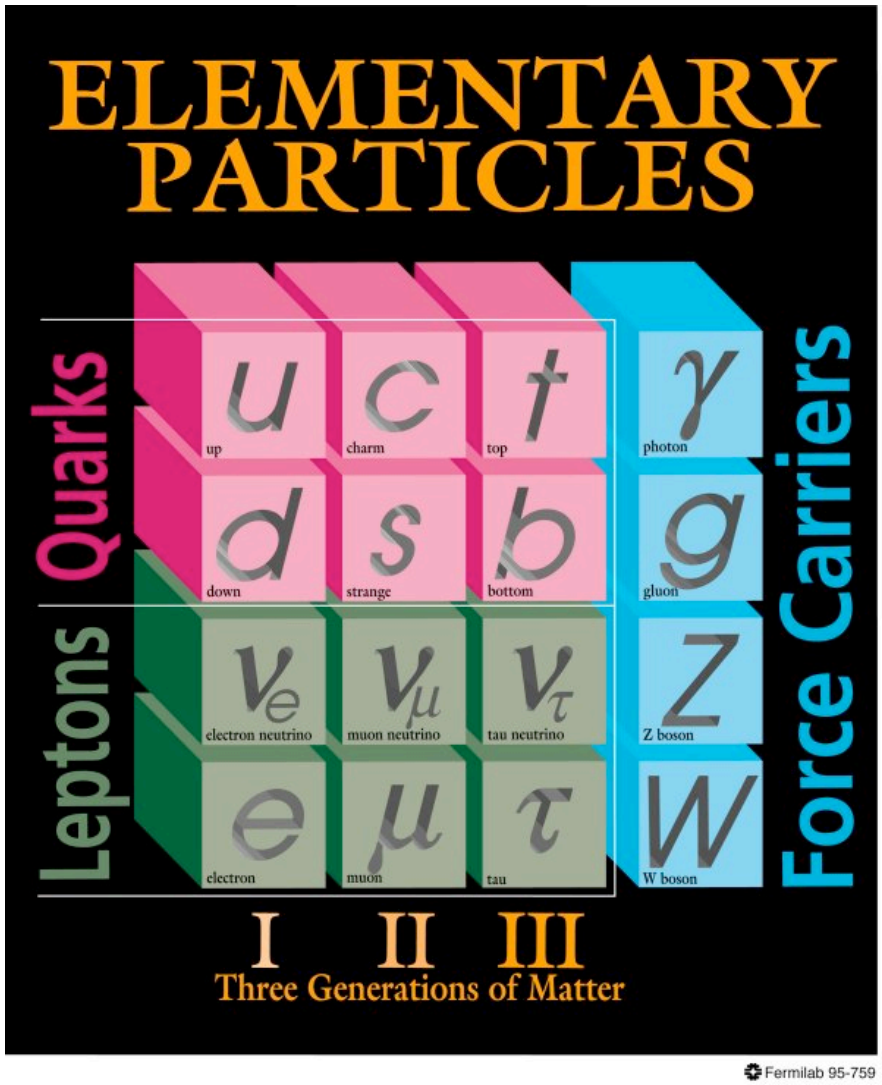
FNAL

Outline

- The Standard Model
- The Tevatron and the DØ Detector
- Diboson Physics
  - The SM Prediction
  - Trilinear Gauge Boson Couplings (TGC)
  - New Physics with Dibosons
- Results from D0
  - *WZ* Production
    - Cross Section Measurement
    - *WWZ* Coupling Limits
  - *W*γ Production
    - Radiation Amplitude Zero (RAZ)
- Final Remarks

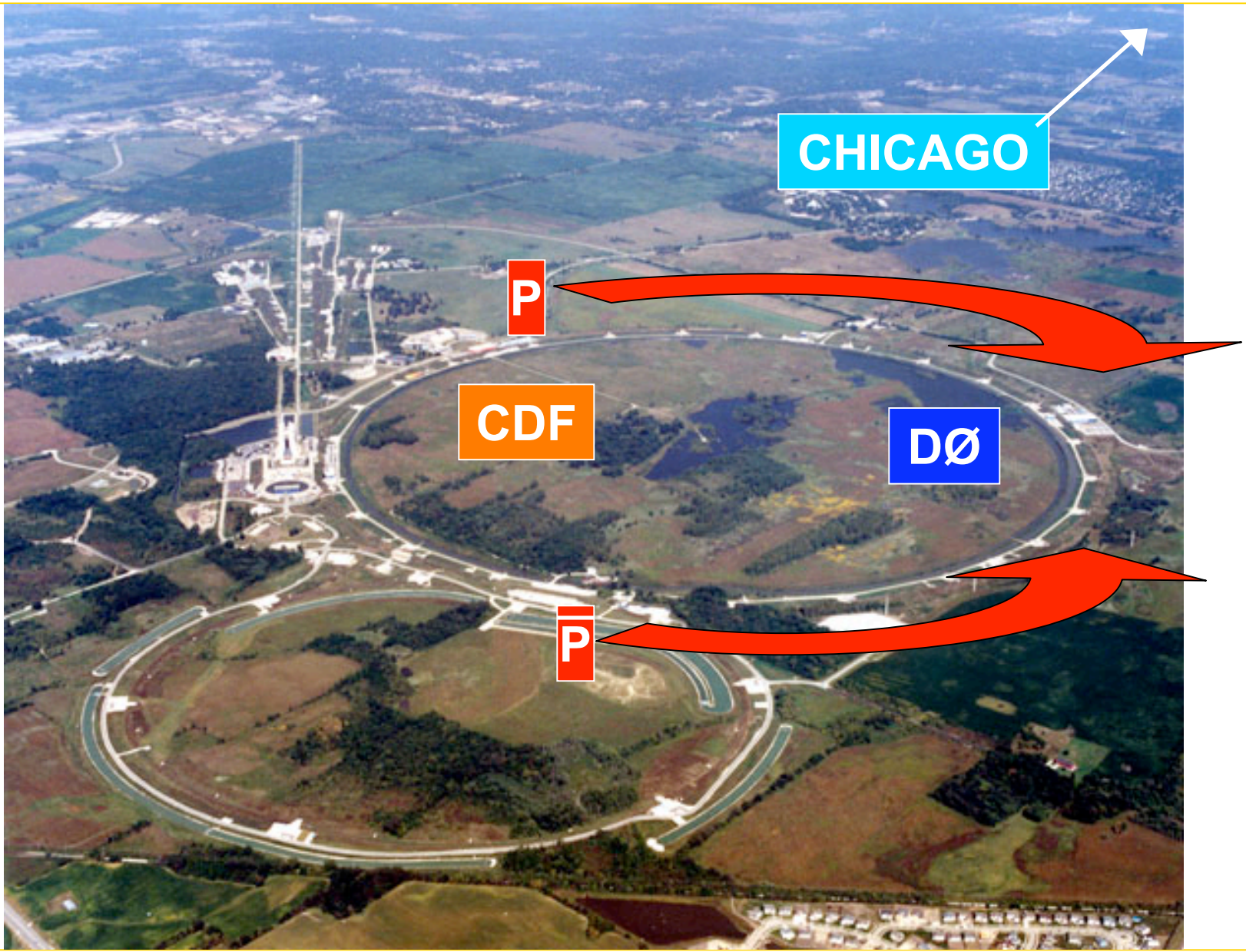


The Standard Model (SM)



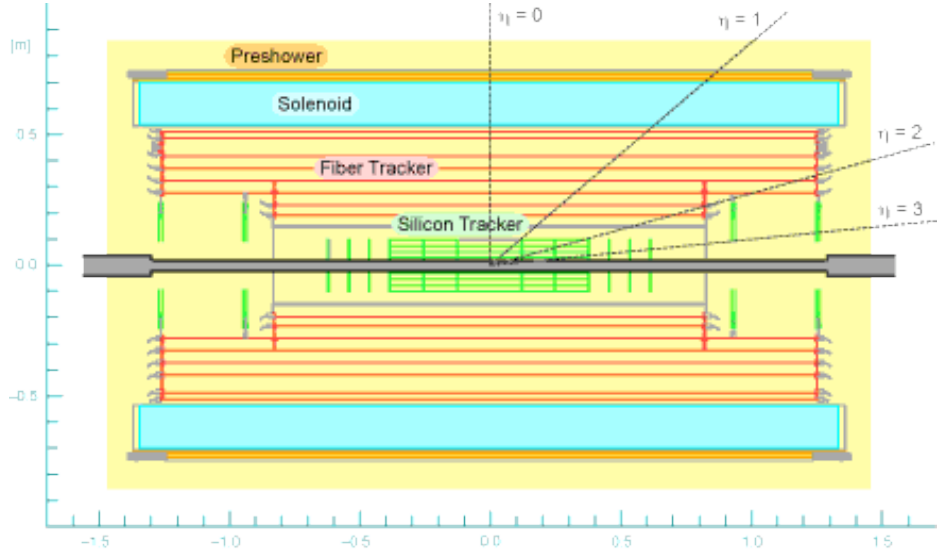
- The Standard Model (SM) predicts dibosons
- Three Generations of particles (quarks and leptons)
- Bosons are the Force Carriers
  - Photon and gluon are massless
  - The W and Z are massive, they interact directly

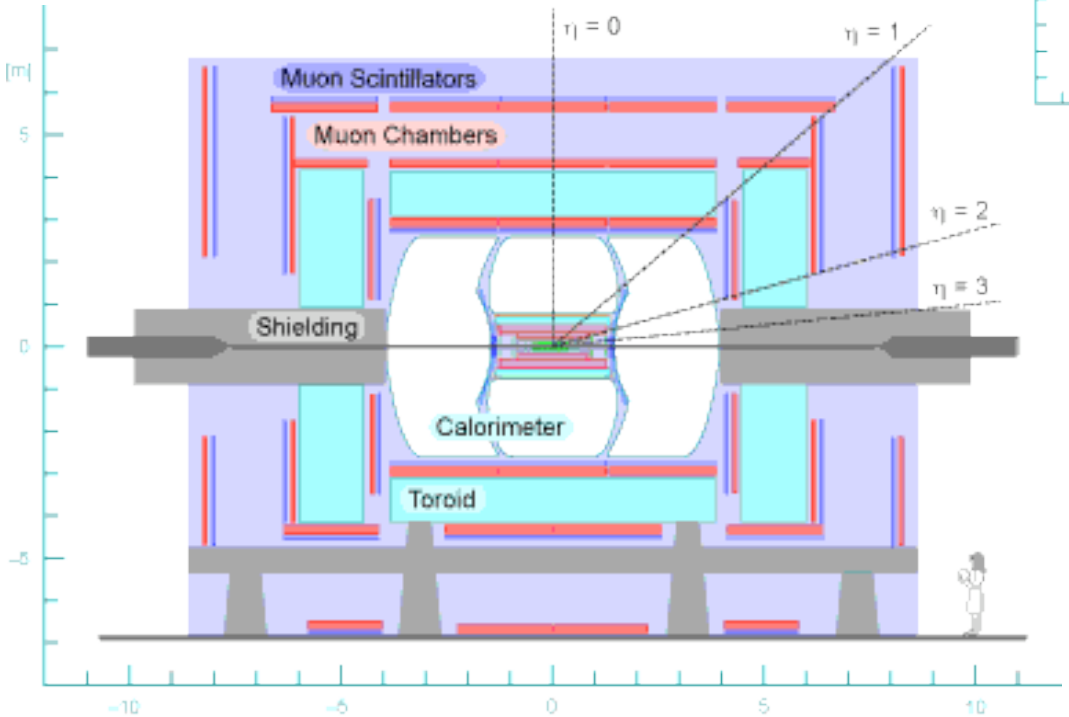
The Fermilab Tevatron



This is DØ

- DØ is a Multipurpose Particle Detector
- Central Tracking
  - Silicon Strips
  - Scintillating Fibers
  - Solenoid Magnet

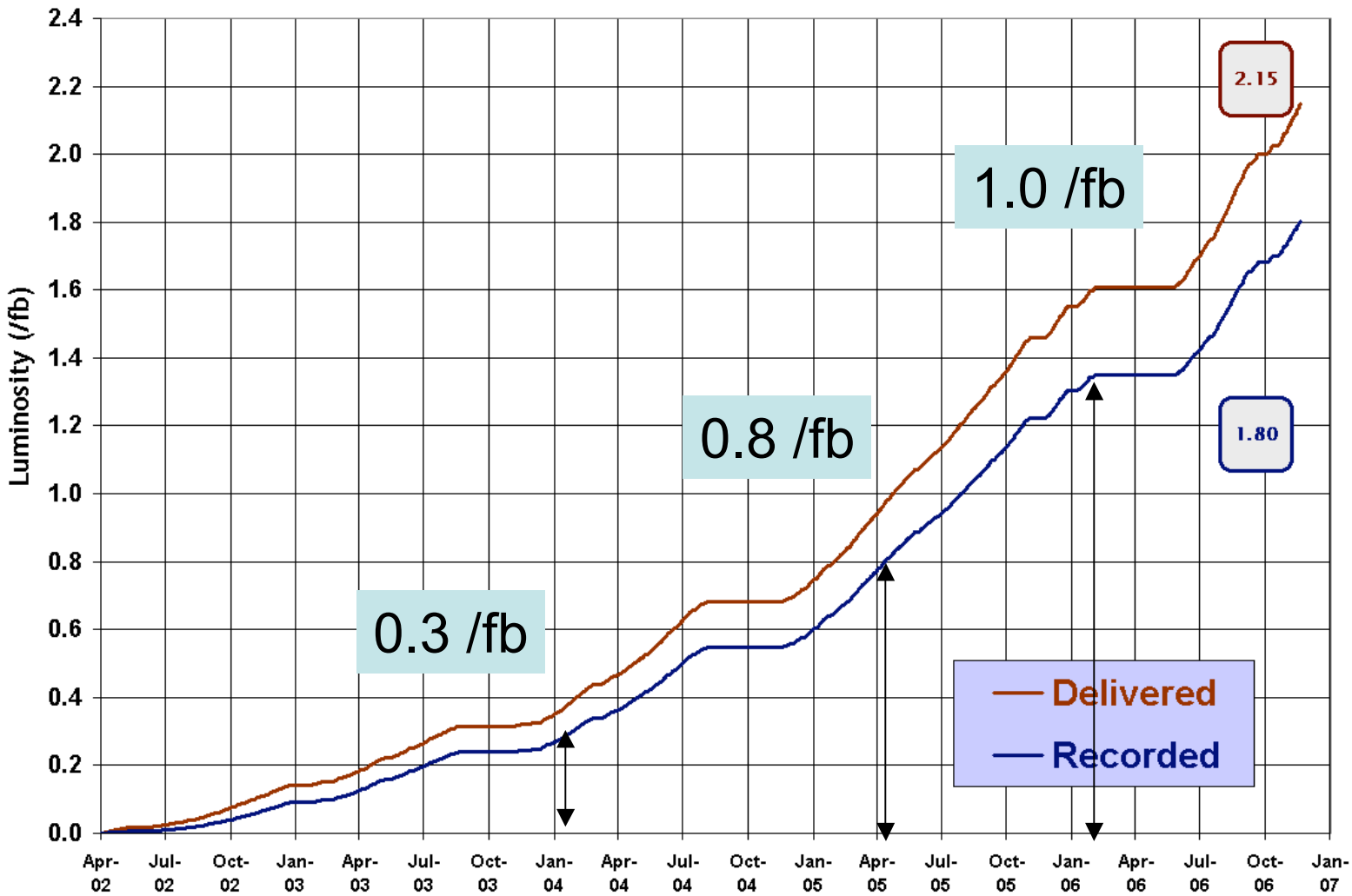




- Electromagnetic and Hadronic Calorimeters
- Muon System
- Toroid Magnet

Run II Integrated Luminosity

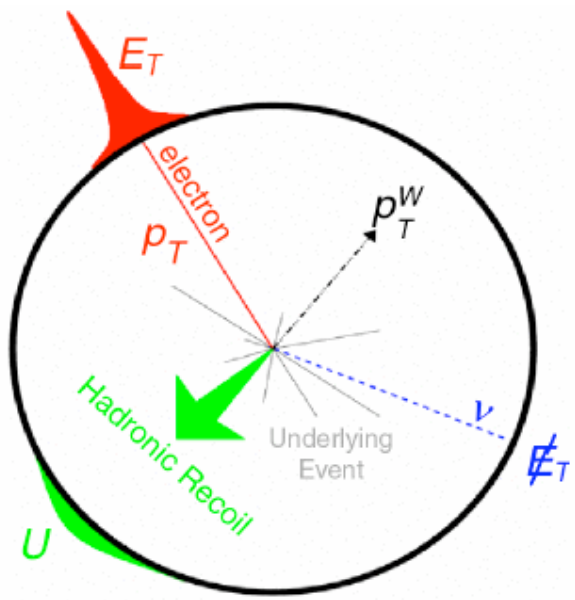
19 April 2002 - 8 December 2006



Experimental Boson Signatures

W Boson

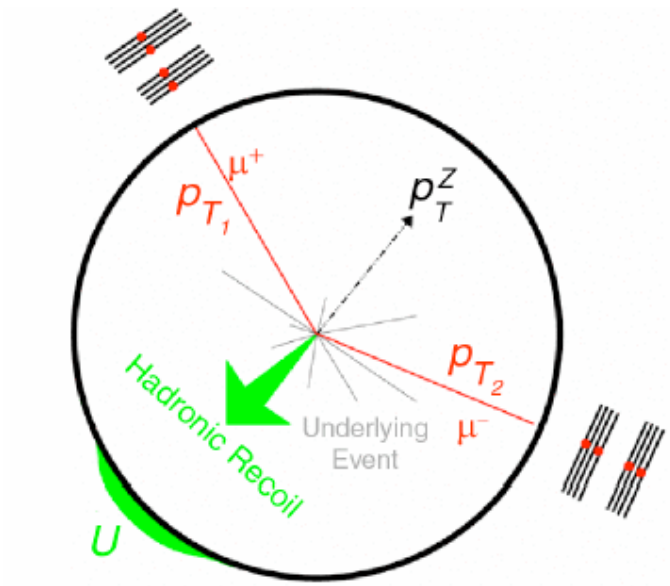
- High E_T *e* or μ
- Large missing E_T



- Decay Modes
  - Leptons: 11%
  - Hadrons: 68 %

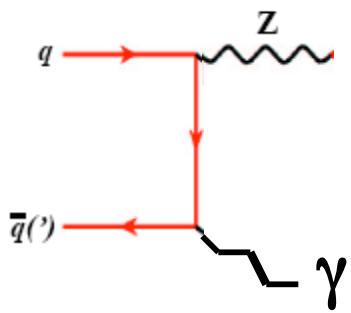
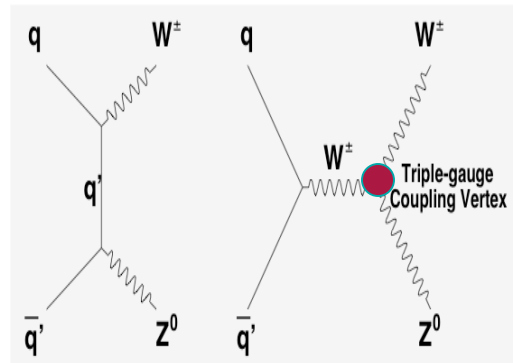
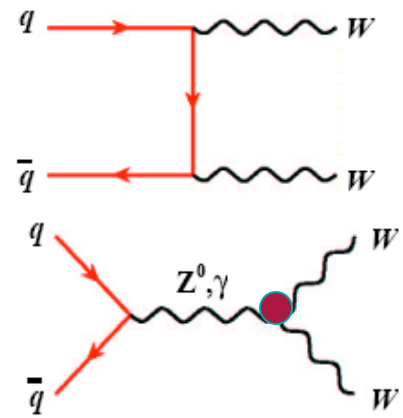
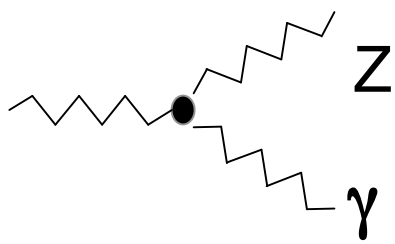
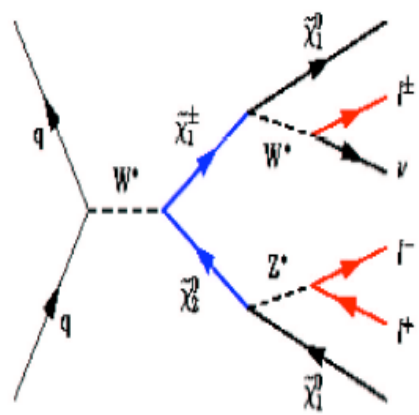
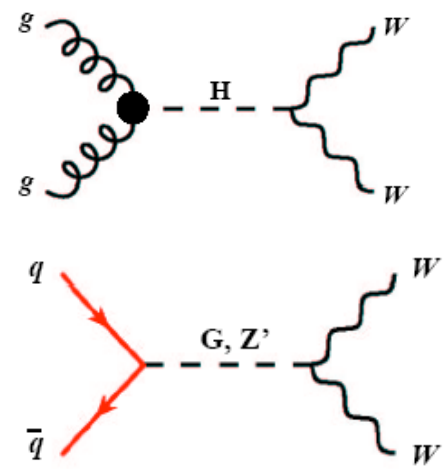
Z Boson

- Two oppositely charged high E_T *e* or μ

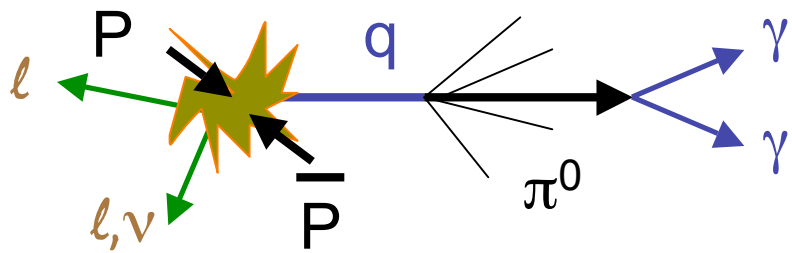


- Decay Modes
  - Leptons: 3.4 %
  - Hadrons: 70 %

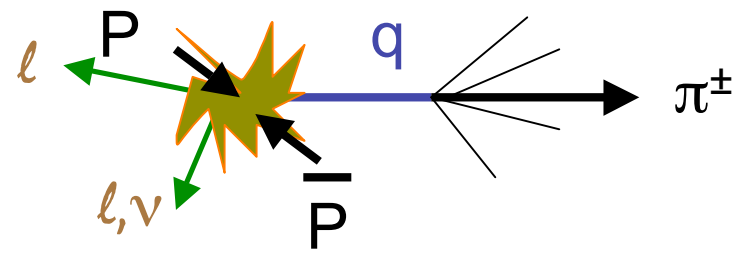
Diboson Physics

Diboson leptonic decays	$Z\gamma \to l^+l^-\gamma$	$ZW \to l^+l^-\nu l$	$WW \to l^+\nu l^-\nu$
SM • Triple-gauge couplings • New physics control samples			
New Physics with Diboson final states	 Beyond SM Zγ interaction	 SUSY signal	

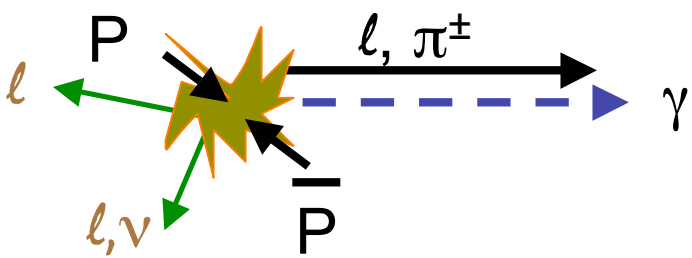
Detector Object Backgrounds



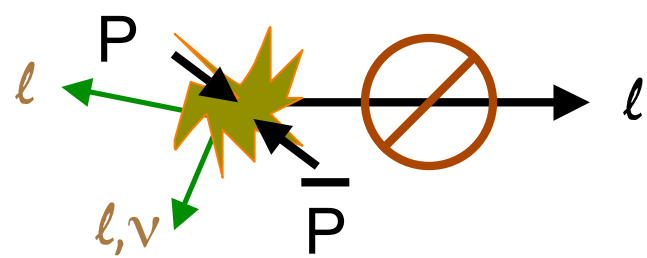
Jet mimics a Photon
Estimated using data



Jet mimics an electron
Estimated using data

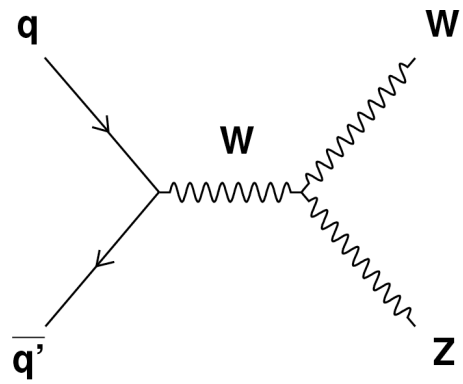


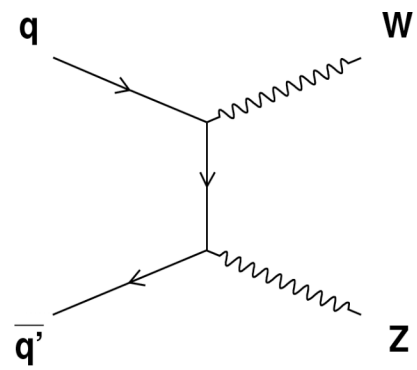
Photon mimics a lepton
Estimated using Data/MC



Lepton mimics a neutrino
Estimated using Monte Carlo

WZ Production in Tevatron





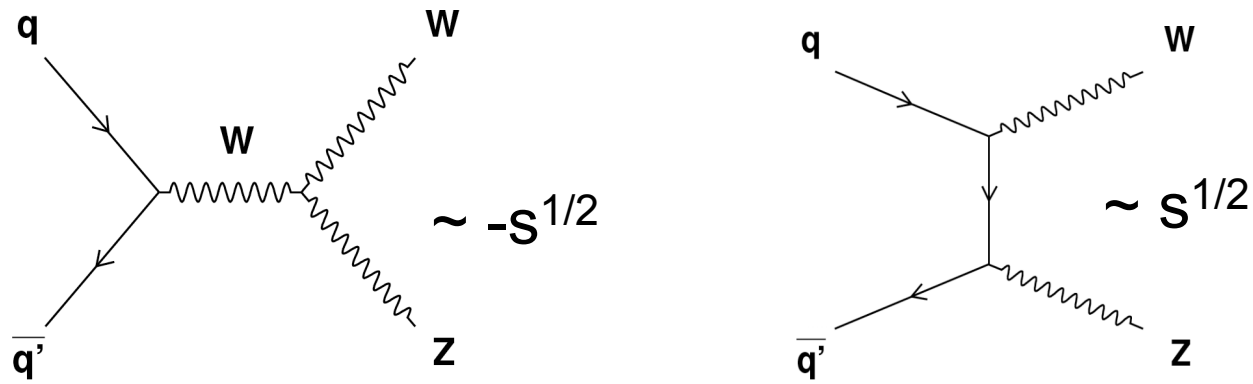
- A unique opportunity to produce both a W and a Z in the final state.
- Never been directly observed before.
- Allows us to probe the WWZ vertex independent of the WWγ couplings.
  - Unlike WW

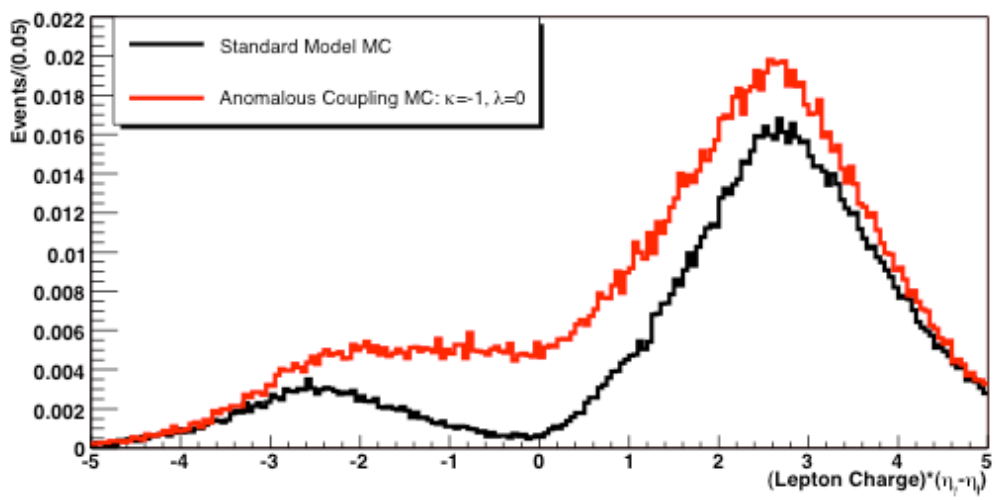
Trilinear Gauge Couplings

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

- V is a Z or γ. $g^1_\gamma = 1$ due to electromagnetic gauge invariance.
- The coupling strengths for a vector boson to couple to itself or another boson.
- Precisely predicted by the SM
  - Any Deviation means New Physics!
- Any significant difference leads to new physics.
  - Anomalous couplings lead to higher cross sections and kinematics
  - Described by a general effective Lagrangian.
    - The SM is a special case of this.
- $\mu_W = (e/2m_W)(g^1_z+\kappa_Z+\lambda_Z)$
- $Q_W = (-e/m^2_W)(\kappa_Z-\lambda_Z)$

Radiation Amplitude Zero



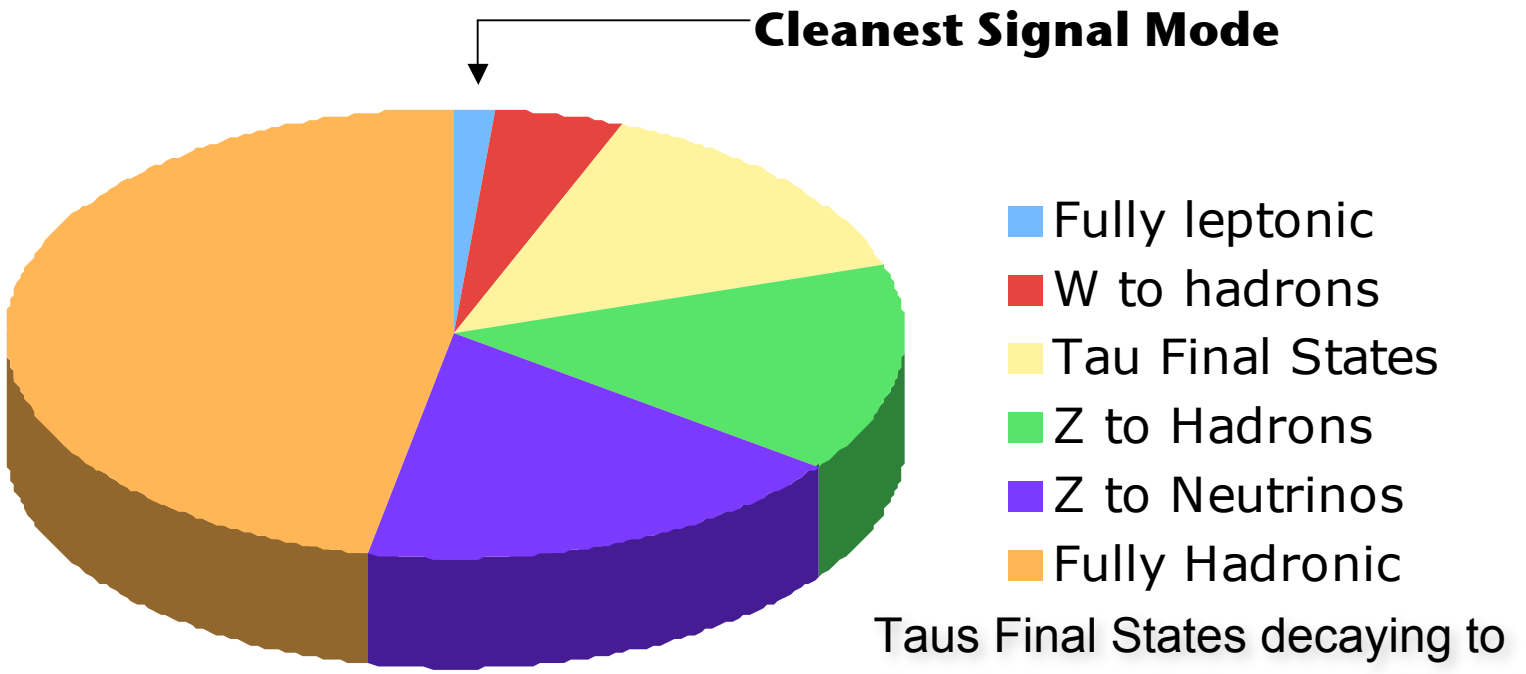


- Radiation Amplitude Zero is a form of the destructive interference between two gauge boson fields.

WZ Decay Channels

- Cleanest signal is from fully leptonic decay (trileptons).
  - Small branching ratio: 0.37% per channel, 1.435 ± 0.013% for four channels.
  - ✚ Smallest backgrounds.

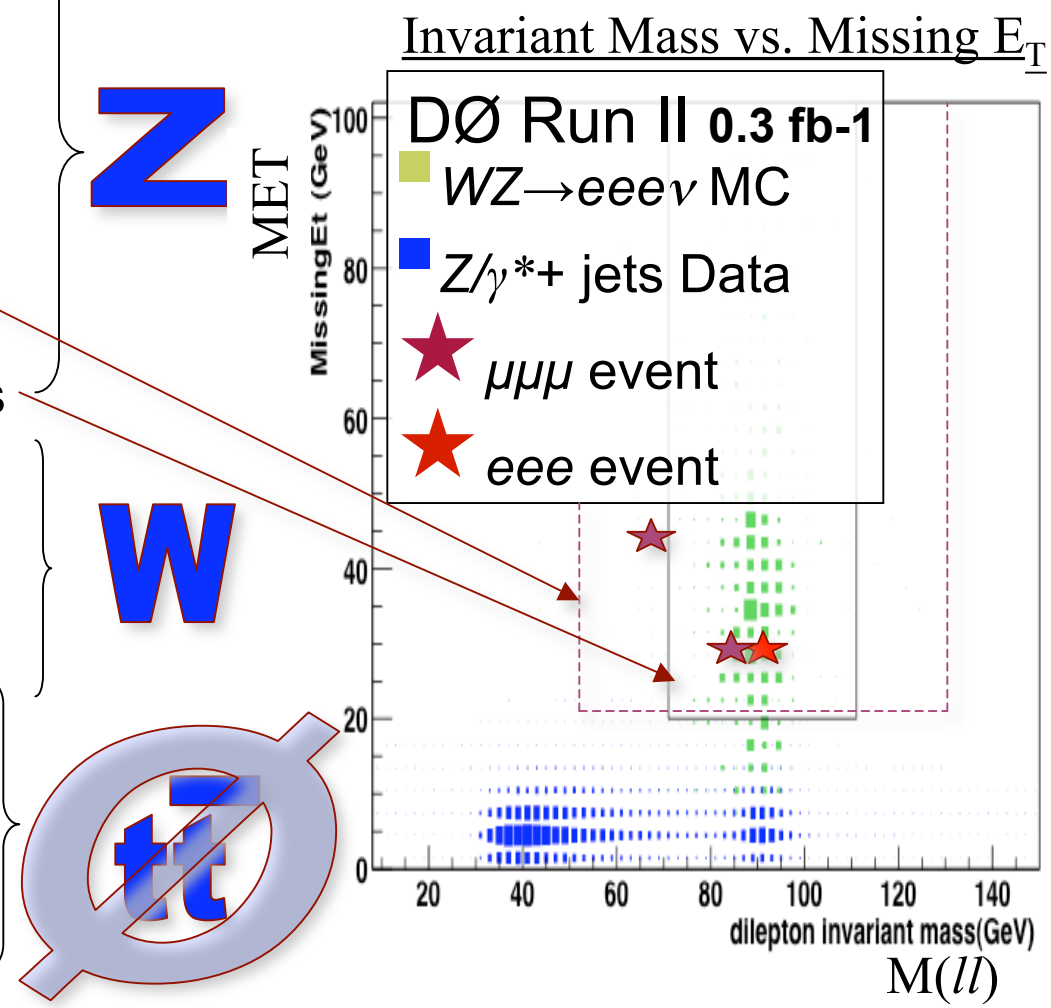
WZ Production Branching Ratios



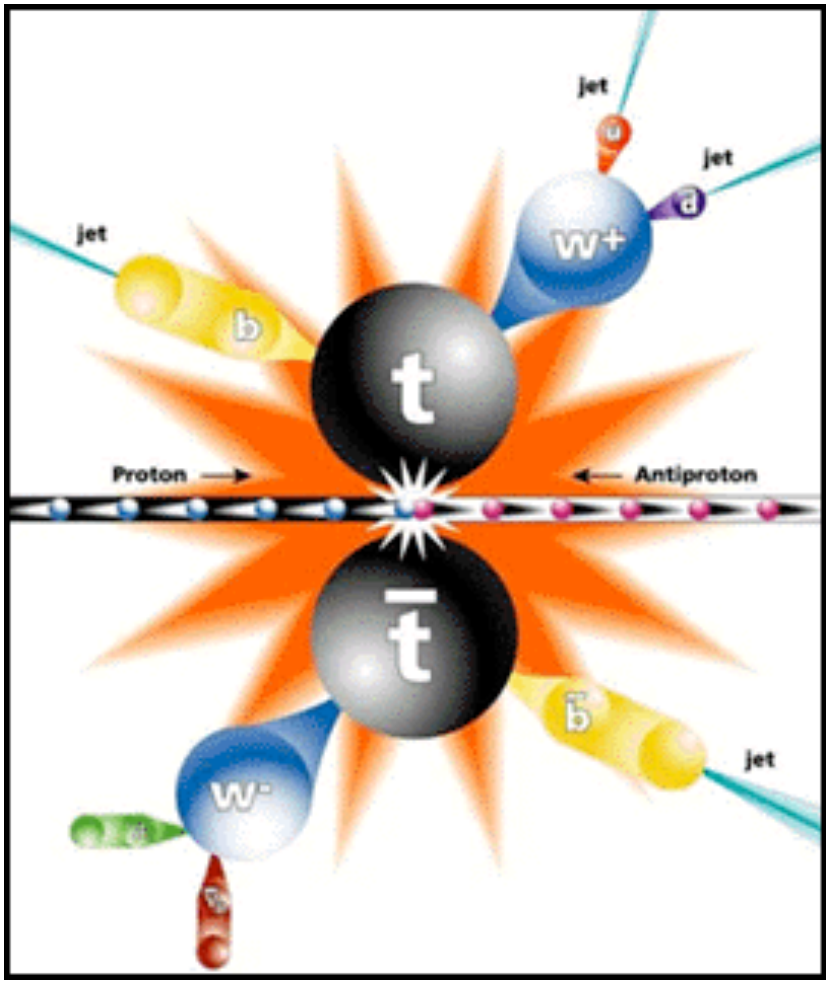
Taus Final States decaying to signal channels is an additional 0.34 %

Signal Selection

- Select 2 leptons
  - p_T > 15 GeV.
- Demand they are within the *Z* mass window.
  - 50-130 GeV/c^2 muons
  - 71-111 GeV/c^2 electrons
- Require MET > 20GeV
- Require at least one more high p_T lepton
- Reject Top events with vector E_T^{HAD} > 50 GeV
  - As measured from the leptons in the event.



tt Backgrounds



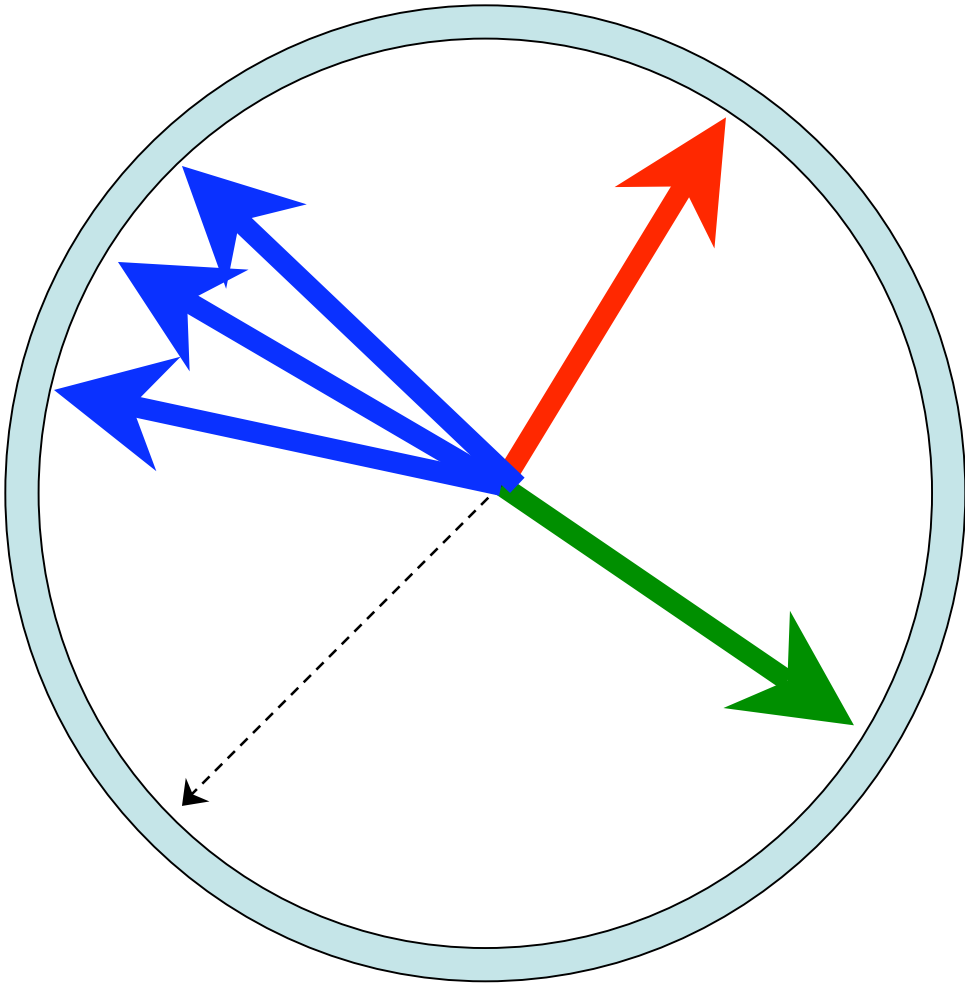
Comes with lots of hadronic energy

Dibosons are rarely associated with that much energy

That Pesky Top quark

VE_T Had

- Vectorially add the E_T of all the leptons in the event.
- Include the missing E_T
- The recoil is from remaining hadronic activity.



$$VE_T \text{ Had} = \Sigma E_{T\ \text{leptons}} + \Sigma \text{missing} E_T = - \Sigma \text{Cal. cells}$$

Change in Analysis

- Essentially the Same analysis as previously
- Kinematic Selection remains the same
- Improved knowledge of detector leads to:
  - Improved muon acceptance.
  - Improved electron ID efficiency.

Muon System Acceptance

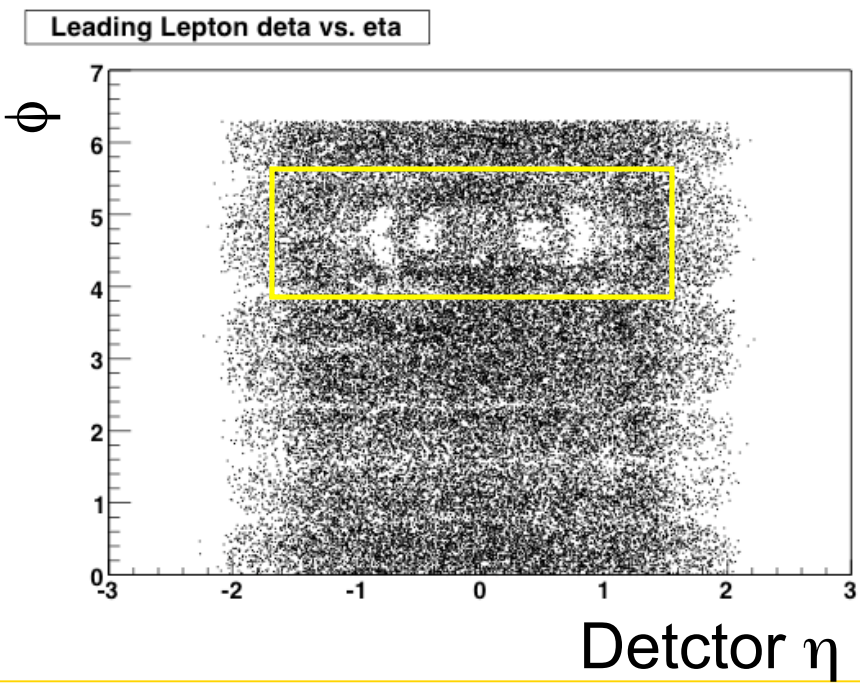
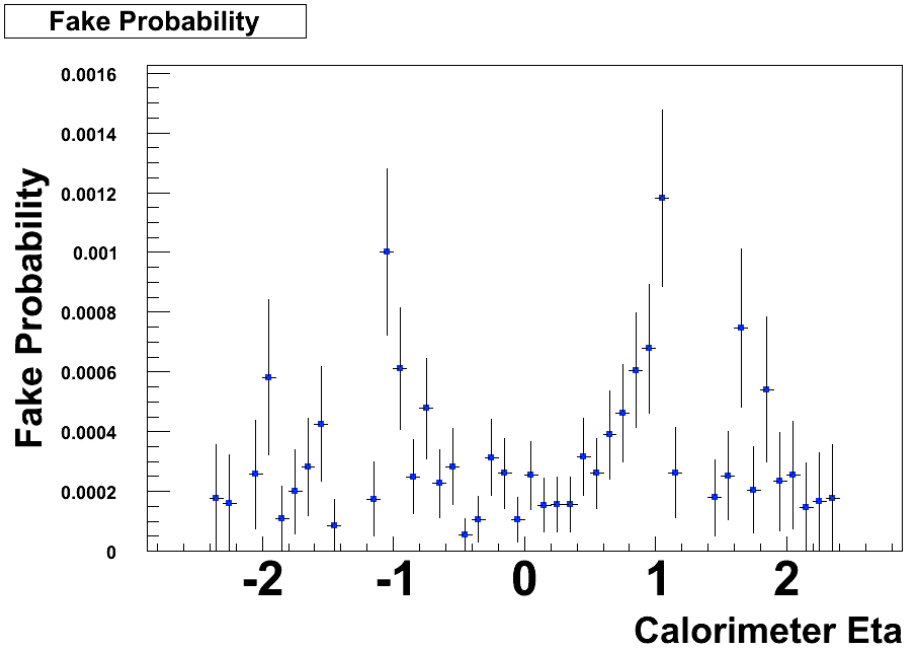


Table of signal efficiency × acceptance for two analyses

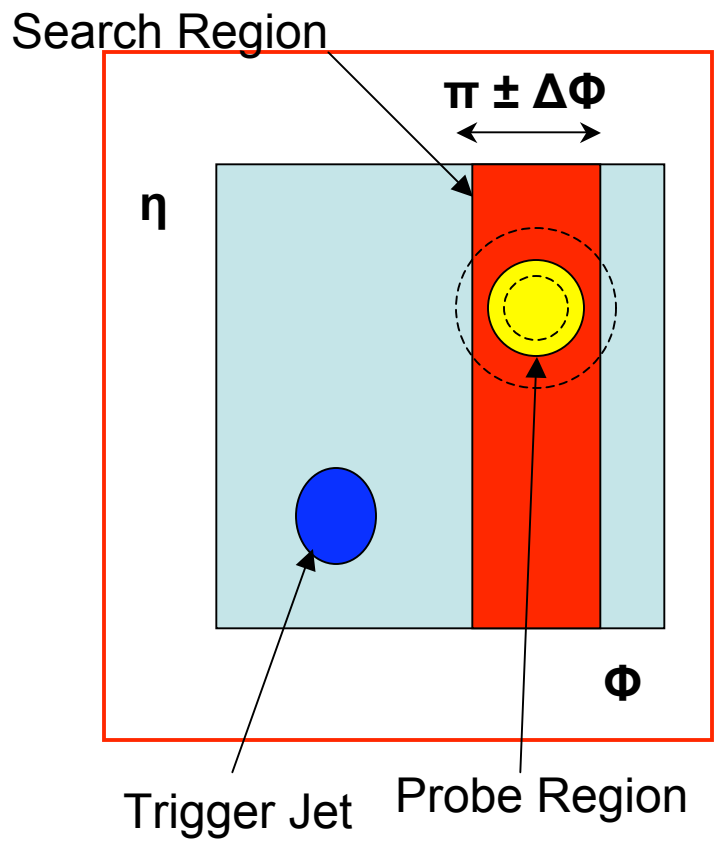
Channel	0.3 fb^{-1}	0.8 fb^{-1}
eee	0.103	0.158
$ee\mu$	0.117	0.167
$\mu\mu e$	0.139	0.175
$\mu\mu\mu$	0.163	0.205

Fake Rate Determination: Electrons

- Trigger jet is a good jet.
- Probe is back to back in Phi, but has search region limited in R.
- Requires some kind of jet object to be present

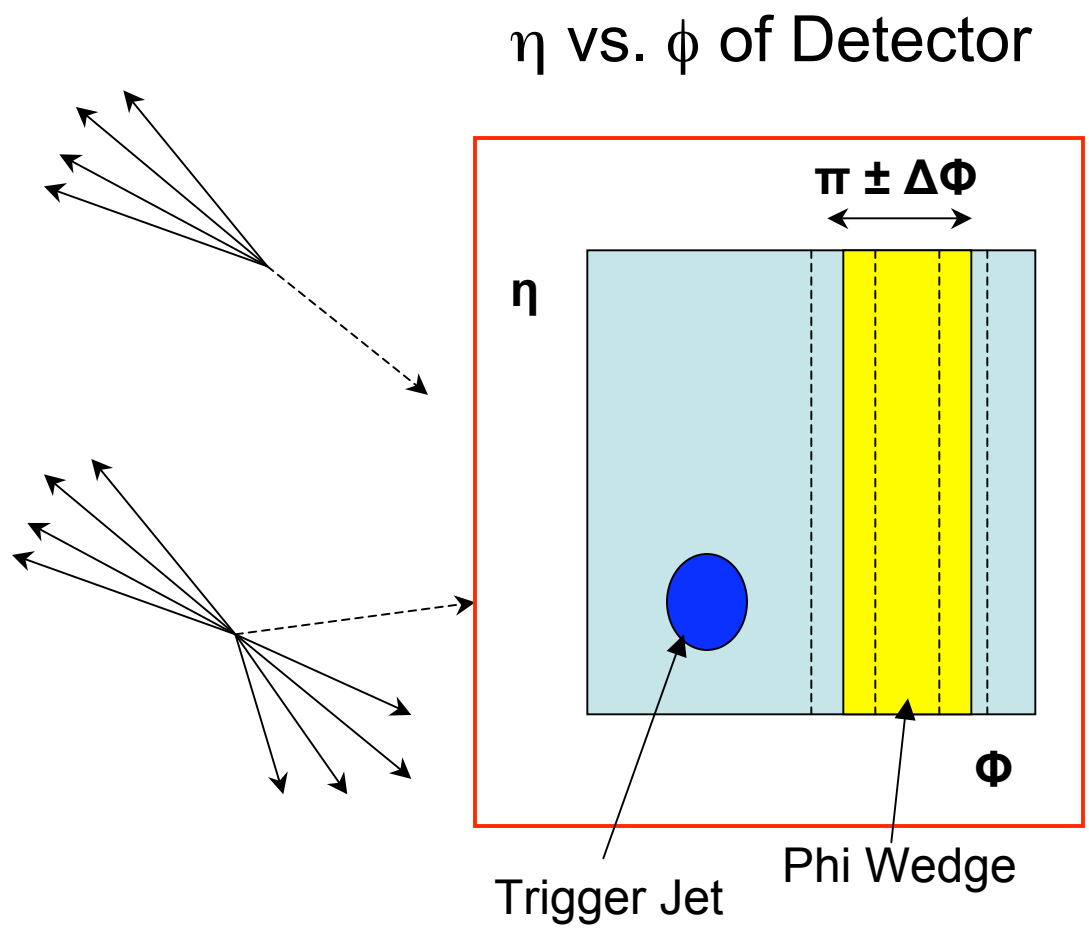


η vs. ϕ of Detector



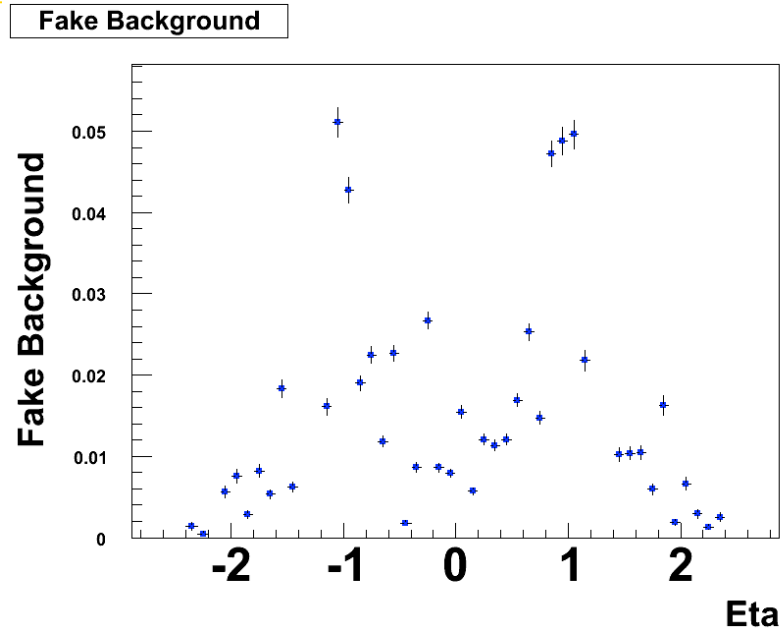
Fake Rate Determination: Muons

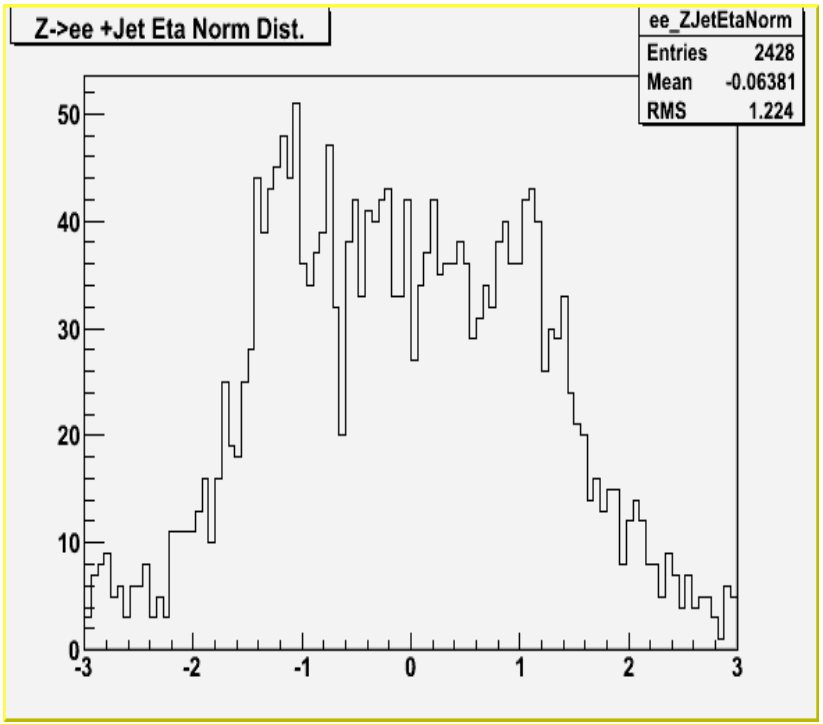
- Trigger jet is a good jet in central region
- Probe region is a ϕ wedge of the detector.
- Jet object is not required to be present.
- Statistics limited
  - Use a flat fake rate
  - $4\times10^{-5}\pm1\times10^{-5}$



QCD Normalizations

- Multiply Fake Rates by Z+Jets sample.

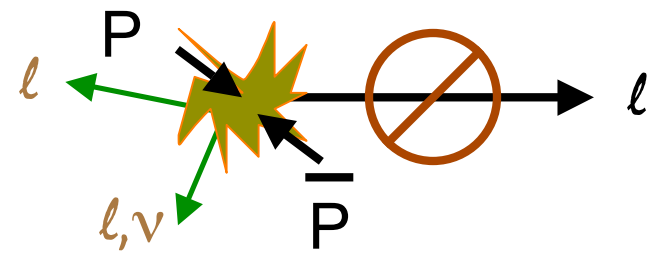




Channel	QCD Background
eee	0.70±0.06
eeμ	0.08±0.02
μμe	0.70±0.06
μμμ	0.08±0.02
Total	1.56±0.09

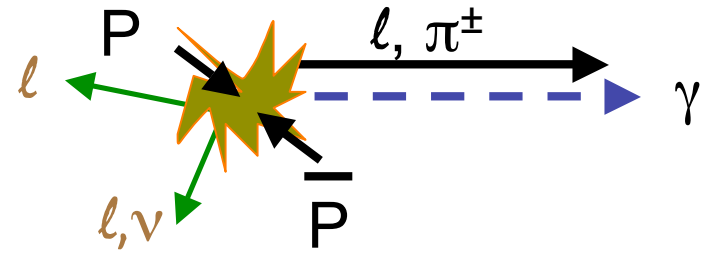
ZZ Background

- Yet to be discovered process.
- Use MC to determine acceptance.
- Normalize to signal sample's luminosity.



Channel	ZZ background
eee	0.57±0.01
eeμ	0.22±0.02
μμe	0.09±0.01
μμμ	0.82±0.08
Total	1.20±0.11

Zγ Background



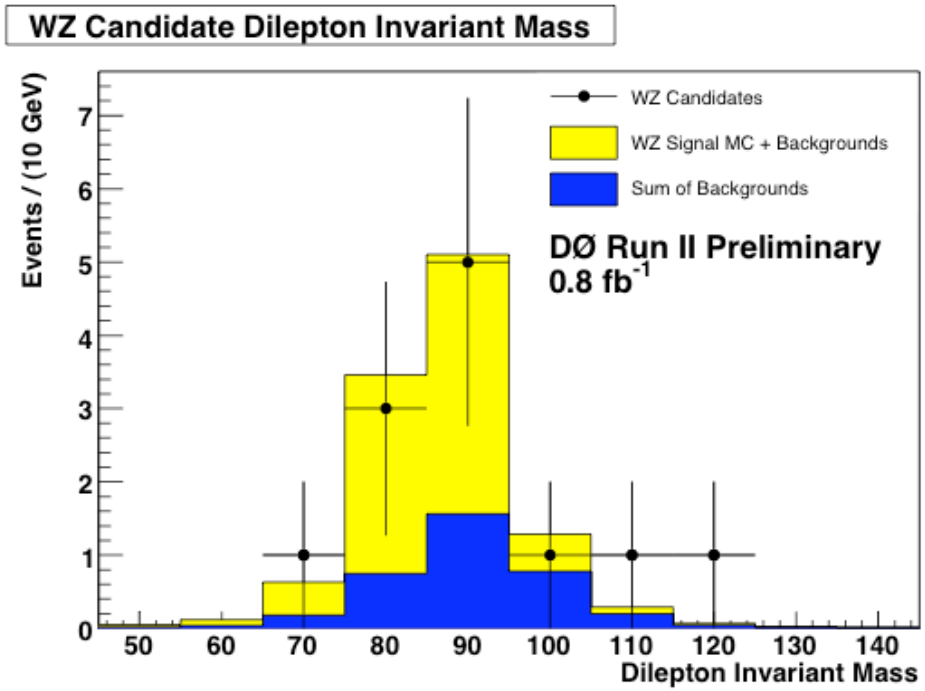
- Use MC to determine acceptance.
- Normalize to signal sample.
- Cross Checks are on going.

Channel	Zγ background
eee	0.001±0.001
μμe	0.001±0.001
Total	0.002±0.001

Backgrounds

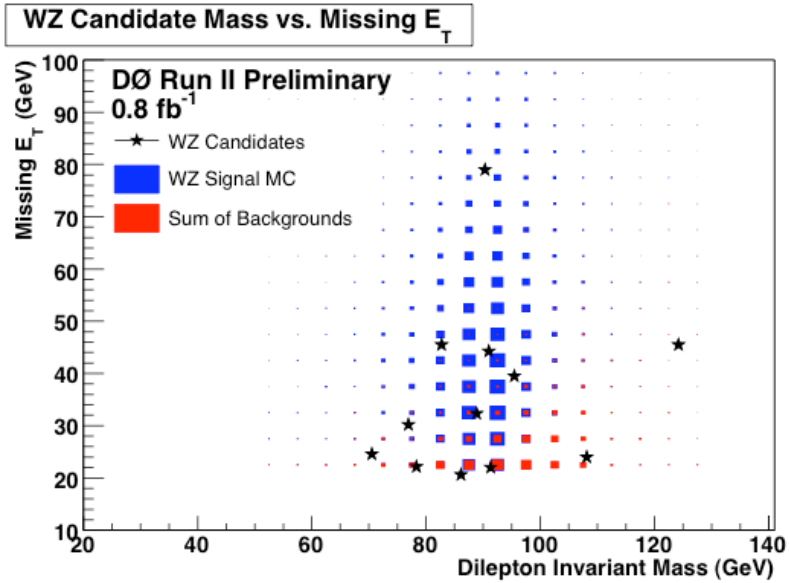
Channel	Source	Estimated Background Events ± Stat. ± Syst.
eee	Z → ee + jets	0.702±0.014±0.056
	ZZ	0.058±0.005±0.006
	Zγ	0.0004±0.0003±0.0001
	ttbar	0.012±0.001±0.036
	Drell-Yan	0.188±0.001±0.036
subtotal		0.960±0.016±0.067
eeμ	e+μ+jets	0.029±0.001±0.002
	Z→ee + jets	0.077±0.002±0.022
	ZZ	0.224±0.004±0.021
	ttbar	0.006±0.006±0.001
	Drell-Yan	0.149±0.001±0.042
subtotal		0.485±0.008±0.052
μμe	Z→μμ + jets	0.699±0.013±0.054
	e+mu+jets	0.004±0.0004±0.001
	ZZ	0.092±0.002±0.009
	Zγ	0.001±0.0007±0.0001
	ttbar	0.005±0.005±0.001
	Drell-Yan	0.161±0.001±0.057
subtotal		0.963±0.015±0.079
μμμ	Z→μμ+jets	0.078±0.002±0.020
	ZZ	0.823±0.011±0.077
	ttbar	<0.0001
	Drell-Yan	0.302±0.002±0.082
subtotal		1.203±0.011±0.143
Total		3.612±0.026±0.202

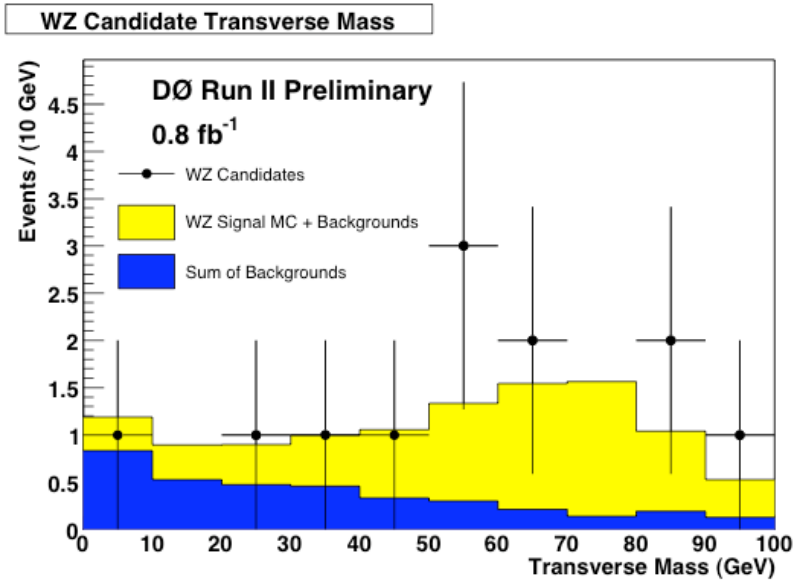
- Major backgrounds are:
  - Fake objects
  - Drell-Yan
  - ZZ->*llll*
- Background + Expected Signal are in good agreement.



Result from D0 on WZ

- σ(ppbar→WZ) prediction 3.68±0.22(scale)±0.12 (PDF) pb
  - MCFM, CTEQ6M
- Find12 events with 800 pb^{-1}
  - expect 7.5 signal events
  - estimate 3.6 background events
- $P(3.61 \rightarrow 12) = 4.2 \times 10^{-4}$
- Significance > 3.3 σ
- σ(ppbar→WZ) = 4.0 + 1.9 - 1.5 pb

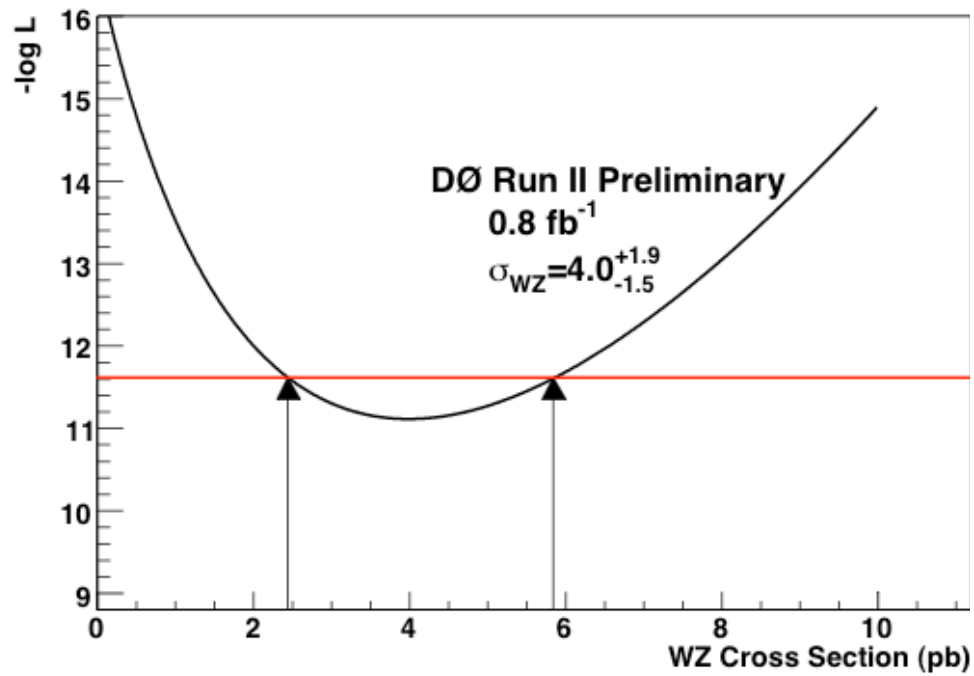




WZ Cross Section Measurement

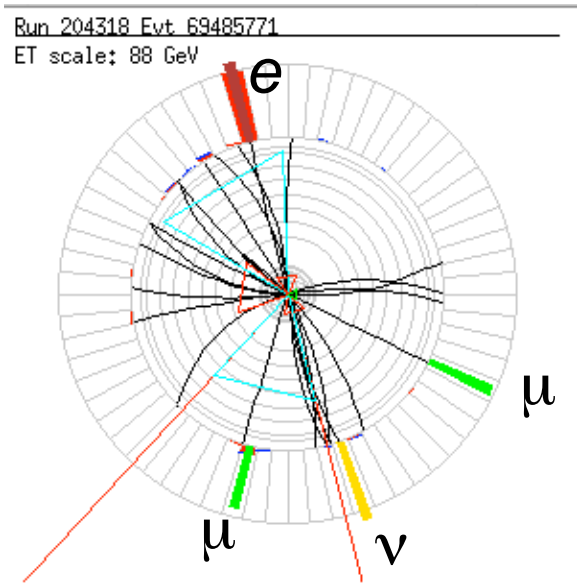
- Using a log-likelihood method
  - Make likelihood in each channel and combine.
  - Minimum is at 4.0 pb
  - 1 σ limits at +1.9 and -1.5
- SM prediction is 3.7±0.3 pb.
- σ_{WZ} **= 4.0 +1.9 -1.5 pb**

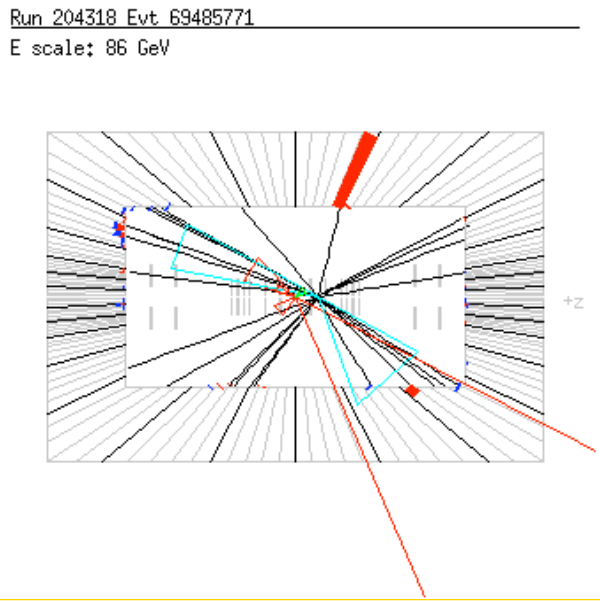
Cross Section Log Likelihood

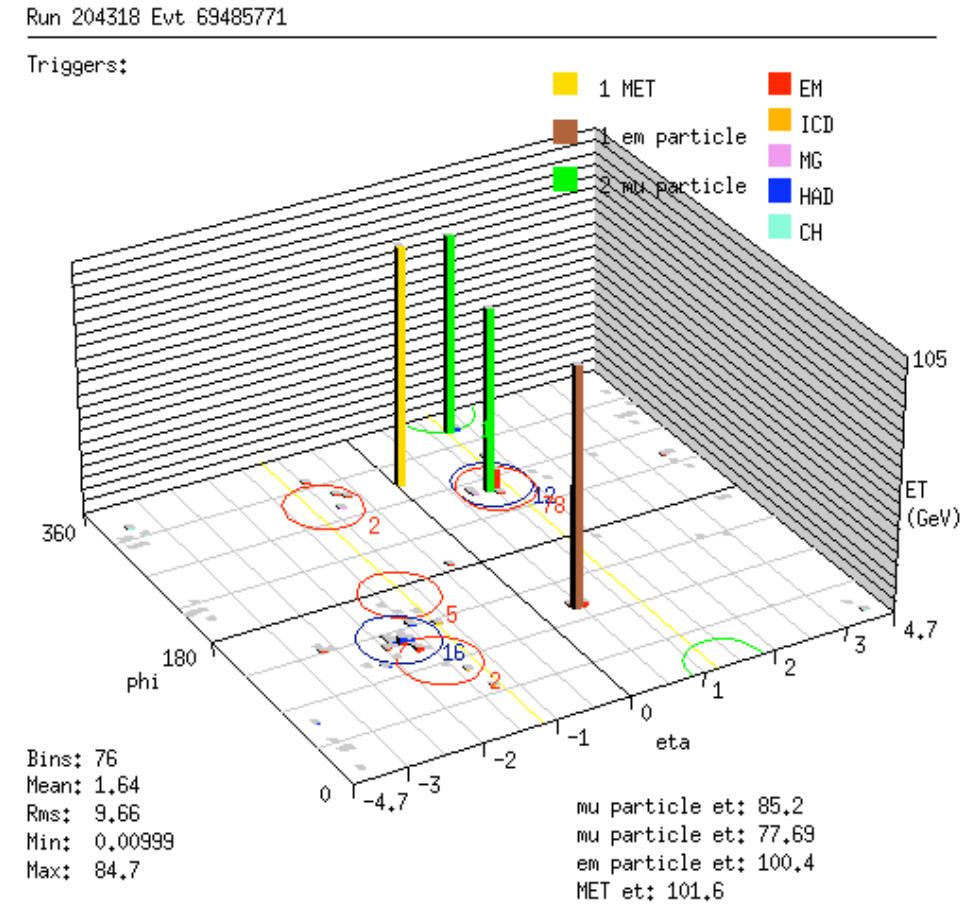


$$L = \int_{\nu_b(1-3\sigma_b)}^{\nu_b(1+3\sigma_b)} \int_{\nu_s(1-3\sigma_s)}^{\nu_s(1+3\sigma_s)} g_b g_s \frac{(x_s\nu_s+x_b\nu_b)^n e^{-(x_s\nu_s+x_b\nu_b)}}{n!} dx_b dx_s$$

Event Views


Run 204318 Evt 69485771
ET scale: 88 GeV
e
μ
μ
ν


Run 204318 Evt 69485771
E scale: 86 GeV


Run 204318 Evt 69485771
Triggers:
1 MET
1 em particle
2 mu particle
EM
ICD
MG
HAD
CH
105
ET (GeV)
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
2
12
78
5
16
2
Bins: 76
Mean: 1.64
Rms: 9.66
Min: 0.00999
Max: 84.7
mu particle et: 85.2
mu particle et: 77.69
em particle et: 100.4
MET et: 101.6

TGC Measurement Procedure

- Generate a grid in coupling space using specialized generators
- Simulate the detector response using a fast Monte Carlo program.
- Calculate the Log likelihood at each point giving a surface.
- Find the 1-D & 2-D 95% C.L. Limits on the Triple Gauge Couplings(TGCs).
- Shown is a LLH fit of WWZ couplings Δg^1_Z vs. λ_Z

Characterized by effective Lagrangian
3 CP Conserving SM Parameters:

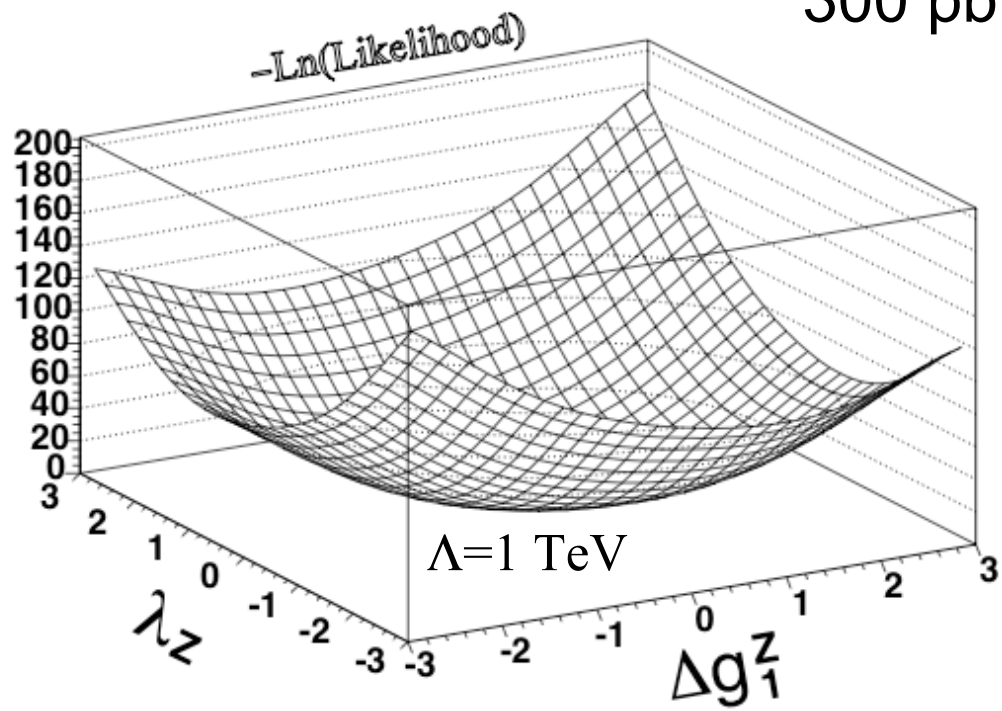
$\lambda_Z = 0$

$\Delta\kappa_Z = 0 \quad (\Delta\kappa_Z = \kappa_Z - 1)$

$\Delta g_1^Z = 0 \quad (\Delta g_1^Z = g_1^Z - 1)$

Δg_1^z vs. λ_z

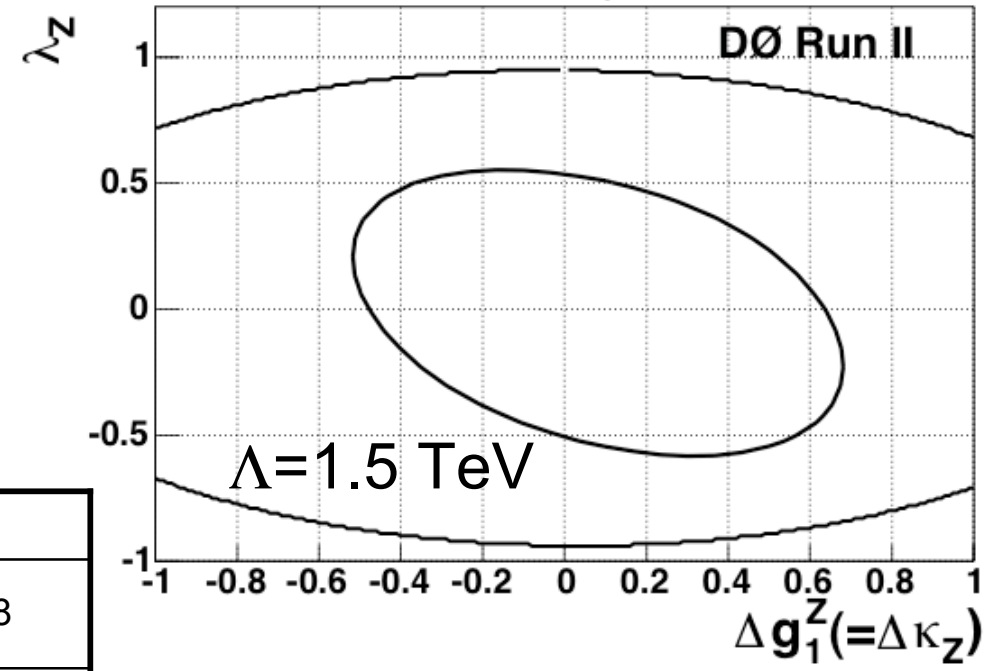
300 pb^{-1}



WWZ Coupling Strength Measurements

- Using 300 pb^{-1} data
- Found 3 events
- Expected 2 signal and 1 background
- Set Limits on WWZ TGCs

2-D Coupling Limits

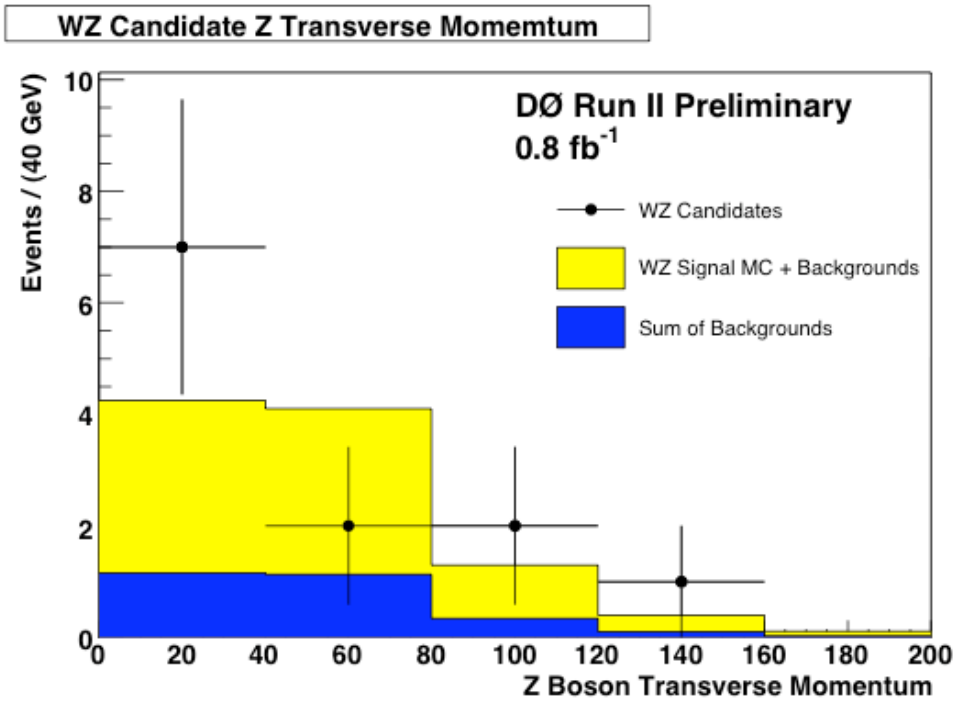


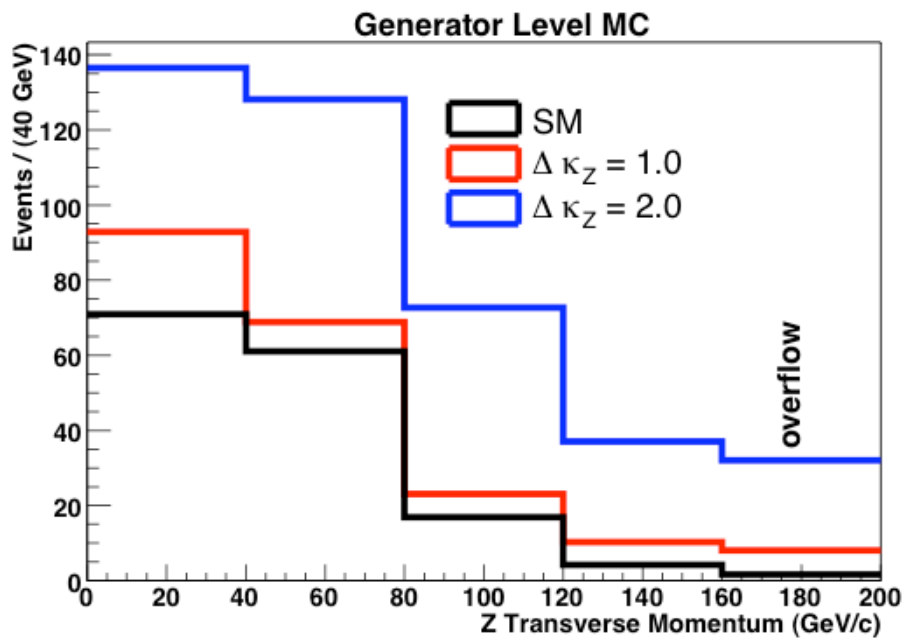
1-D Coupling Limits

Condition	Λ=1.0 TeV	Λ=1.5 TeV
$\Delta g^Z_1=\Delta\kappa_Z=0$	$-0.53<\lambda_Z<0.56$	$-0.48<\lambda_Z<0.48$
$\lambda_Z=\Delta\kappa_Z=0$	$-0.57<\Delta g^Z_1<0.76$	$-0.49<\Delta g^Z_1<0.66$
$\lambda_Z=0$	$-0.49<\Delta g^Z_1=\Delta\kappa_Z<0.66$	$-0.43<\Delta g^Z_1=\Delta\kappa_Z<0.57$
$\lambda_Z=\Delta g^Z_1=0$	$-2.0<\Delta\kappa_Z<2.4$	-

New Method For Measuring Coupling Strengths

- Once cross section is finalized:
  - Take advantage of the *Z* p_T spectrum of *WZ* candidates
  - Improve upon *WWZ* trilinear couplings measurements at hadron collider.

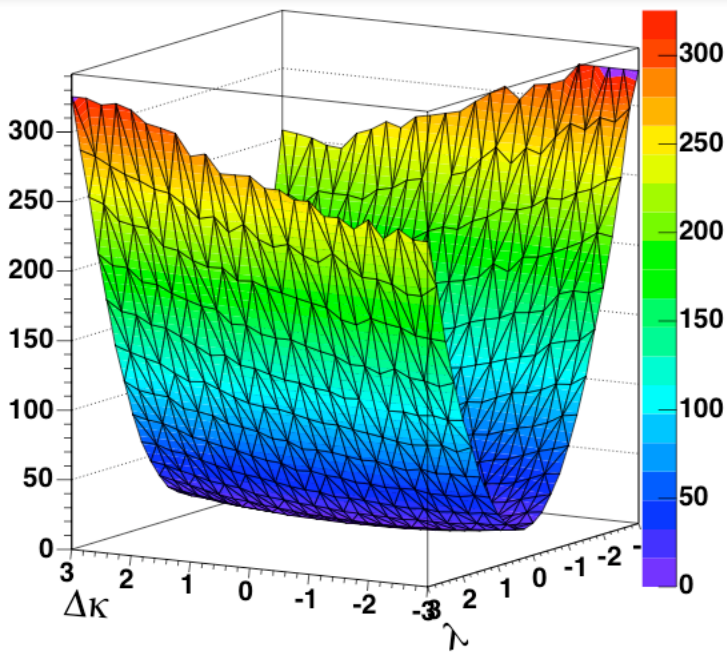


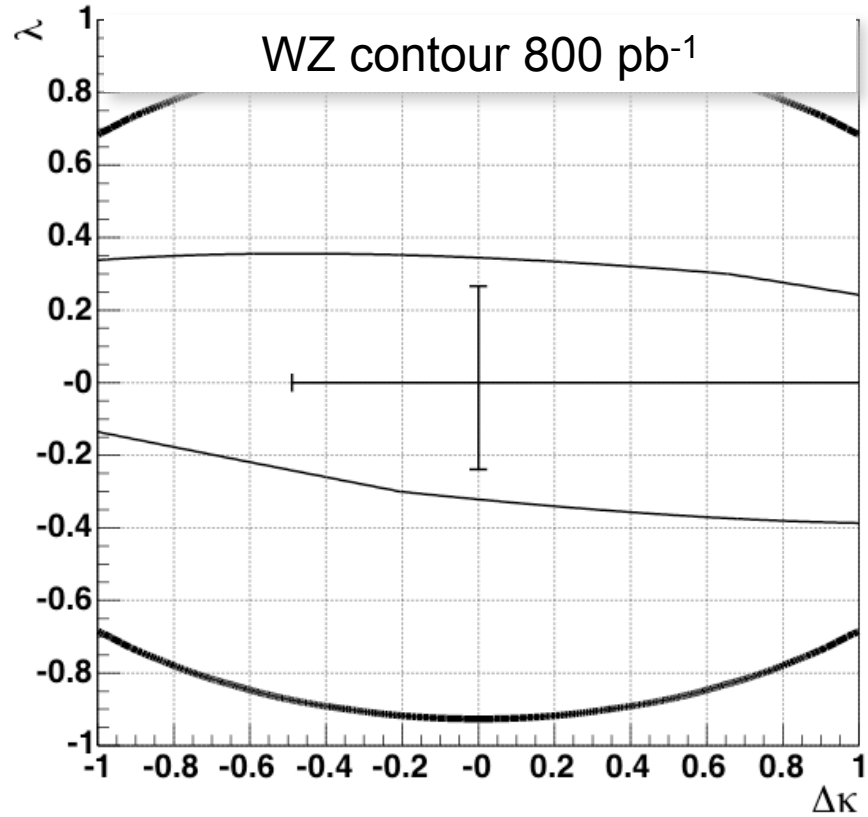


Latest Results

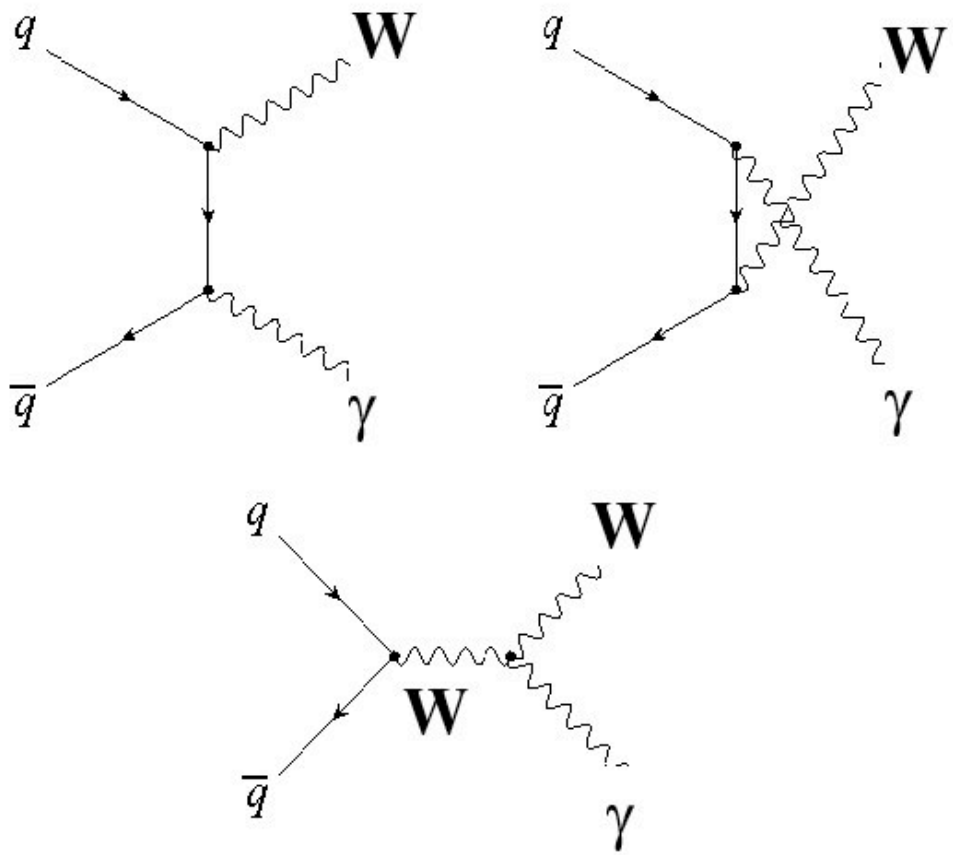
- Used 4 channels to get a final contour.
- Current results are encouraging.
  - Appears improvement by a factor of two.
- All currently work in progress.

WZ Likelihood Grid





$W\gamma$ Introducion



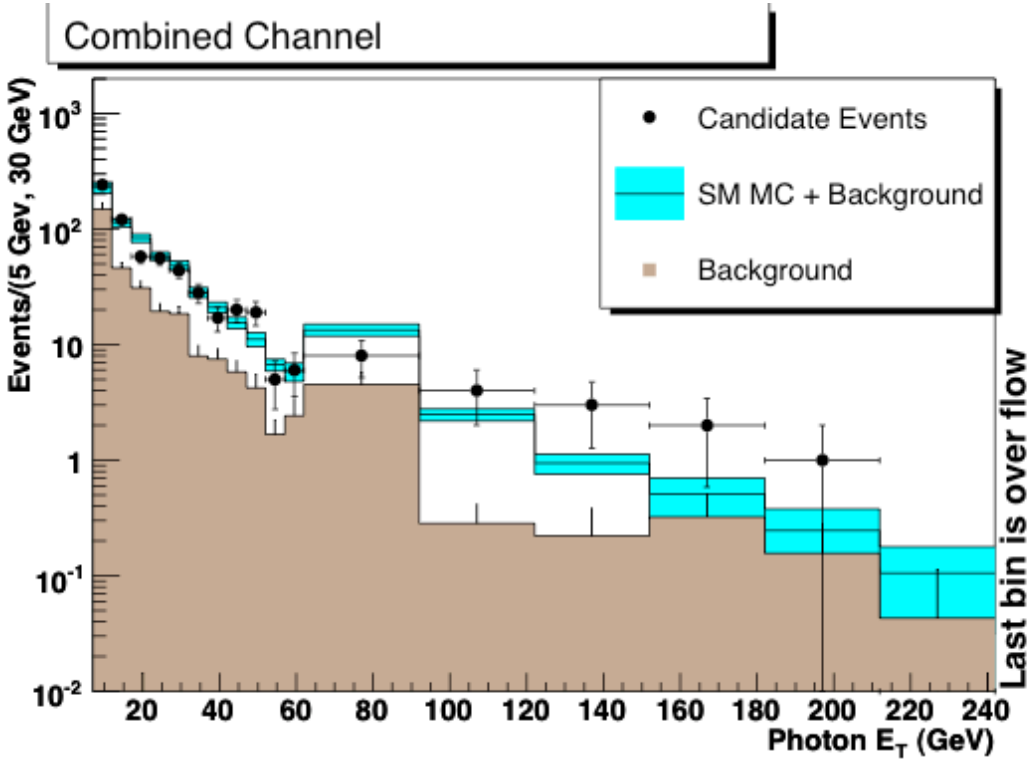
- $WW\gamma$ physics is very similar to WWZ
- The coupling constants behave the same way.

$W\gamma$ Selection

In A Nut Shell

- Event Signature is:
  - High P_T Lepton
  - Missing E_T
  - Isolated Photon
- Leptons are an *e* or an μ
  - Isolated
  - Highly efficient
- Photons start from 7 GeV.
  - Of good quality.
  - Come from same vertex as lepton.
- *Z* Veto
- Three body and Two Body M_T cut

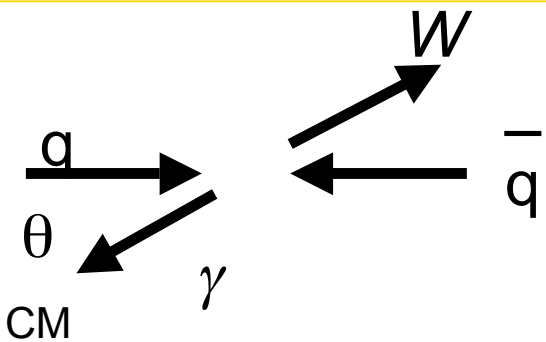
$W\gamma$ Cross Section

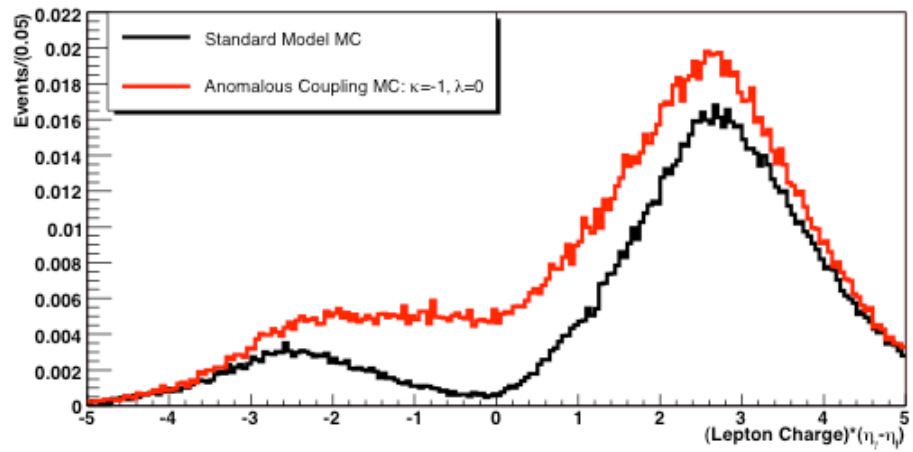


SM 3.21 ± 0.08 pb

- Electron Channel
  - 933 pb^{-1}
  - 205±26 events
  - 3.12±0.49±0.19 pb
- Muon Channel
  - 878 pb^{-1}
  - 130±18 events
  - 3.21±0.49±0.20 pb

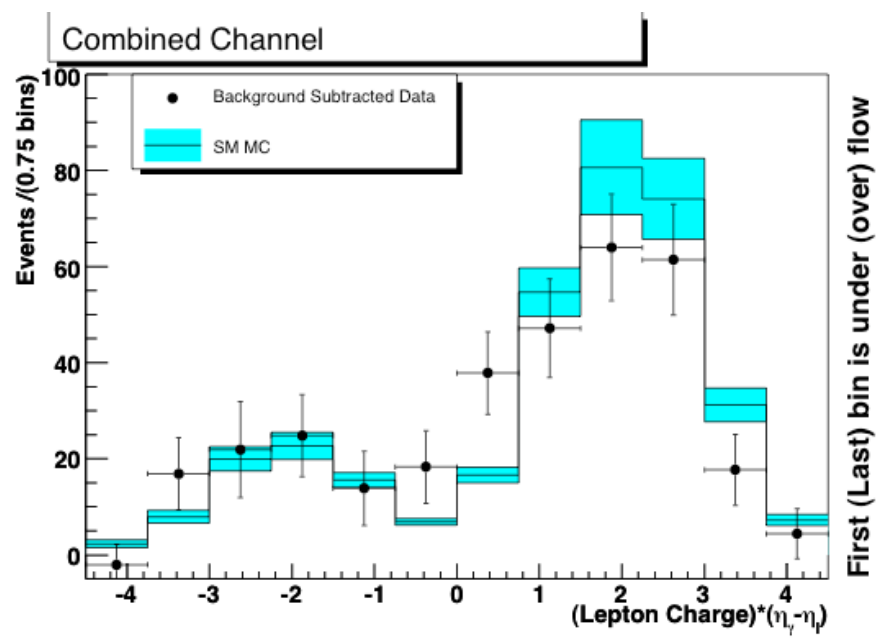
Radiation Amplitude Zero





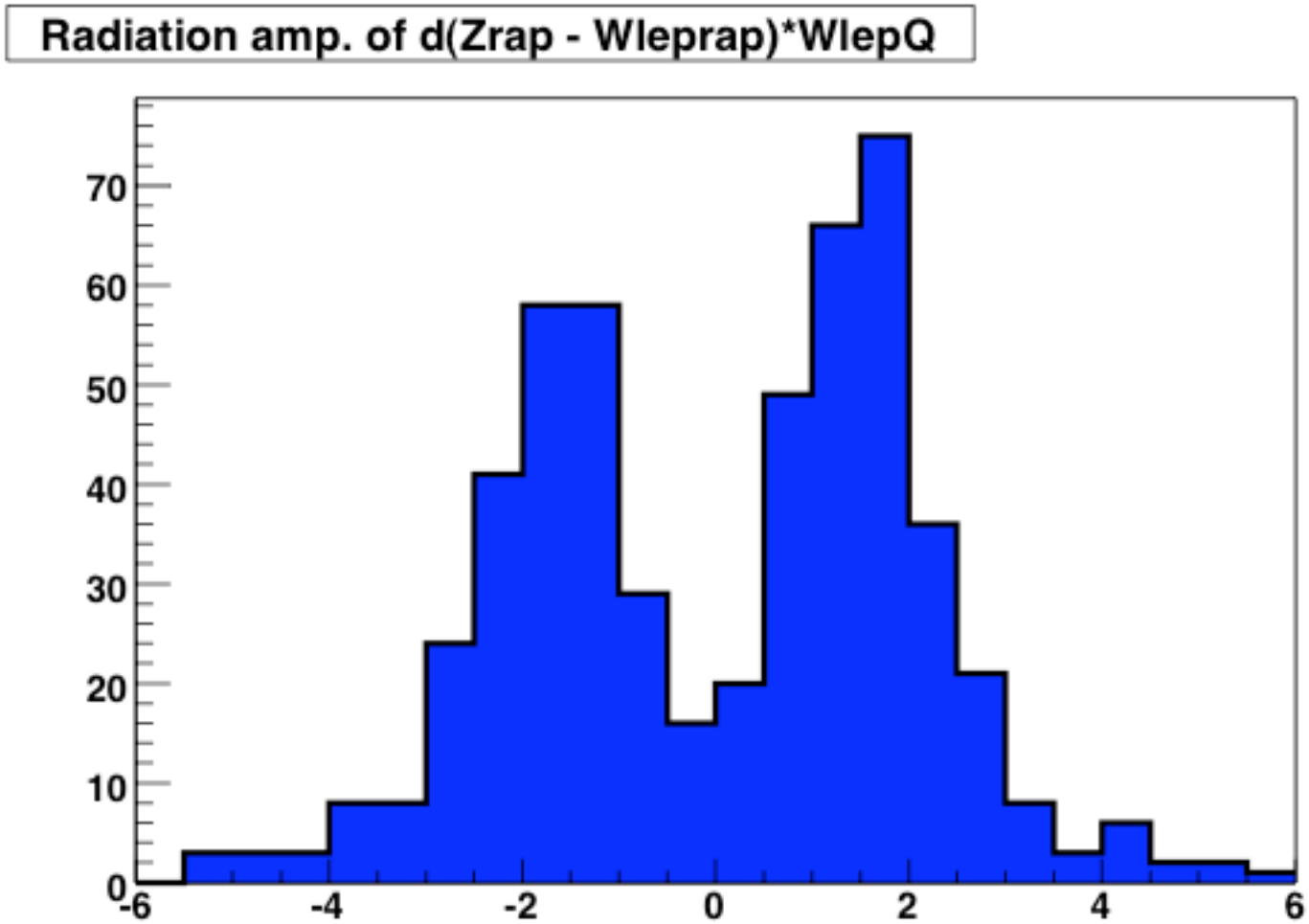
$u\bar{d} \rightarrow W\gamma$ has Zero at $\cos\theta_{CM} = -1/3$

$d\bar{u} \rightarrow W\gamma$ has Zero at $\cos\theta_{CM} = +1/3$



- Zeros originate in $\cos\theta_{CM}$ distribution
- Neutrino creates ambiguity
- Correlations lead to zeros in charge sign rapidy difference.

RAZ For *WZ!*

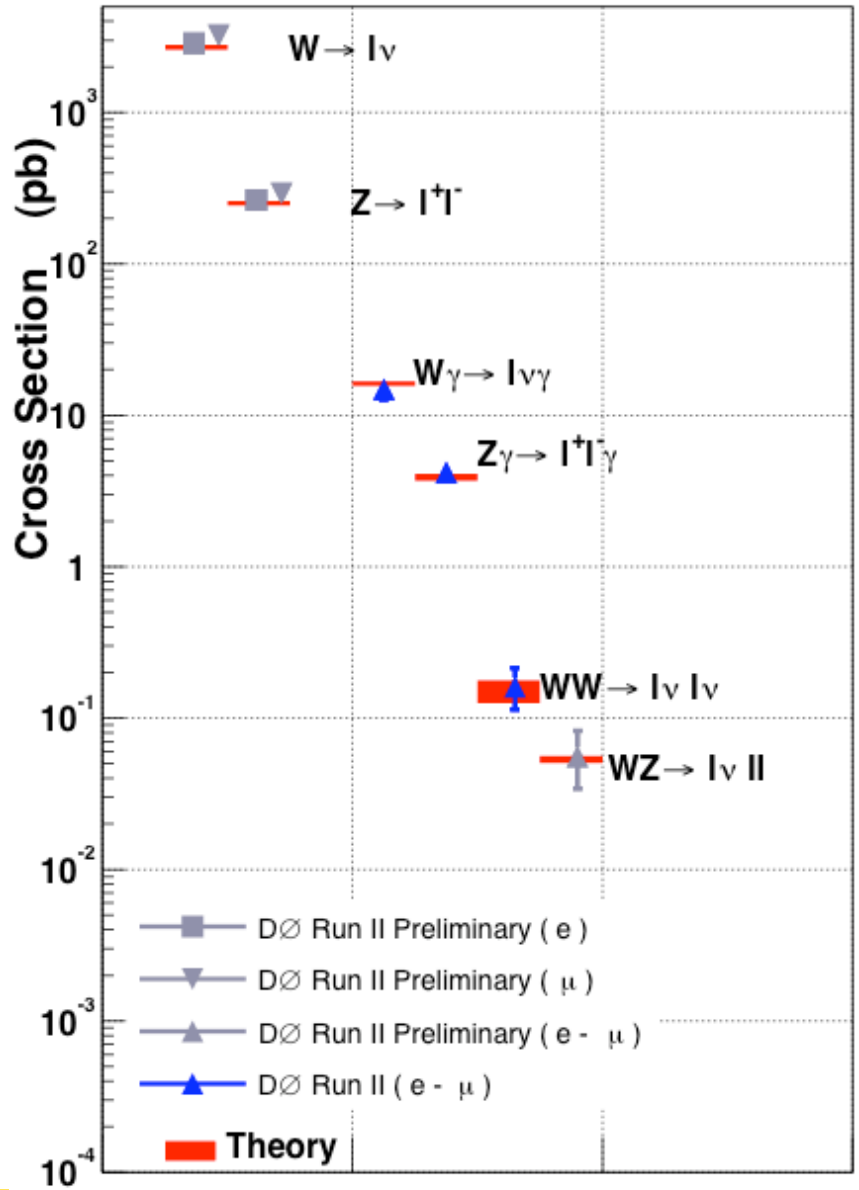


Signed rapidity difference between Z and the W charged lepton.

Several orders of magnitude more luminosity than current have.

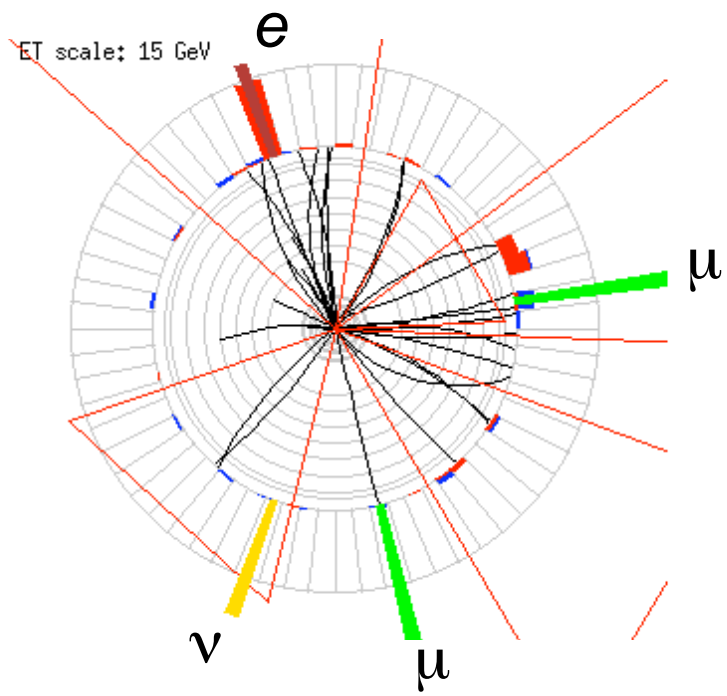
Final Remarks

- There are many new and exciting Electroweak results from the Tevatron
  - First Evidence & observation of WZ production
  - RAZ for Wγ
- More exciting results are soon to come!
- These analyses will be extended at the LHC.

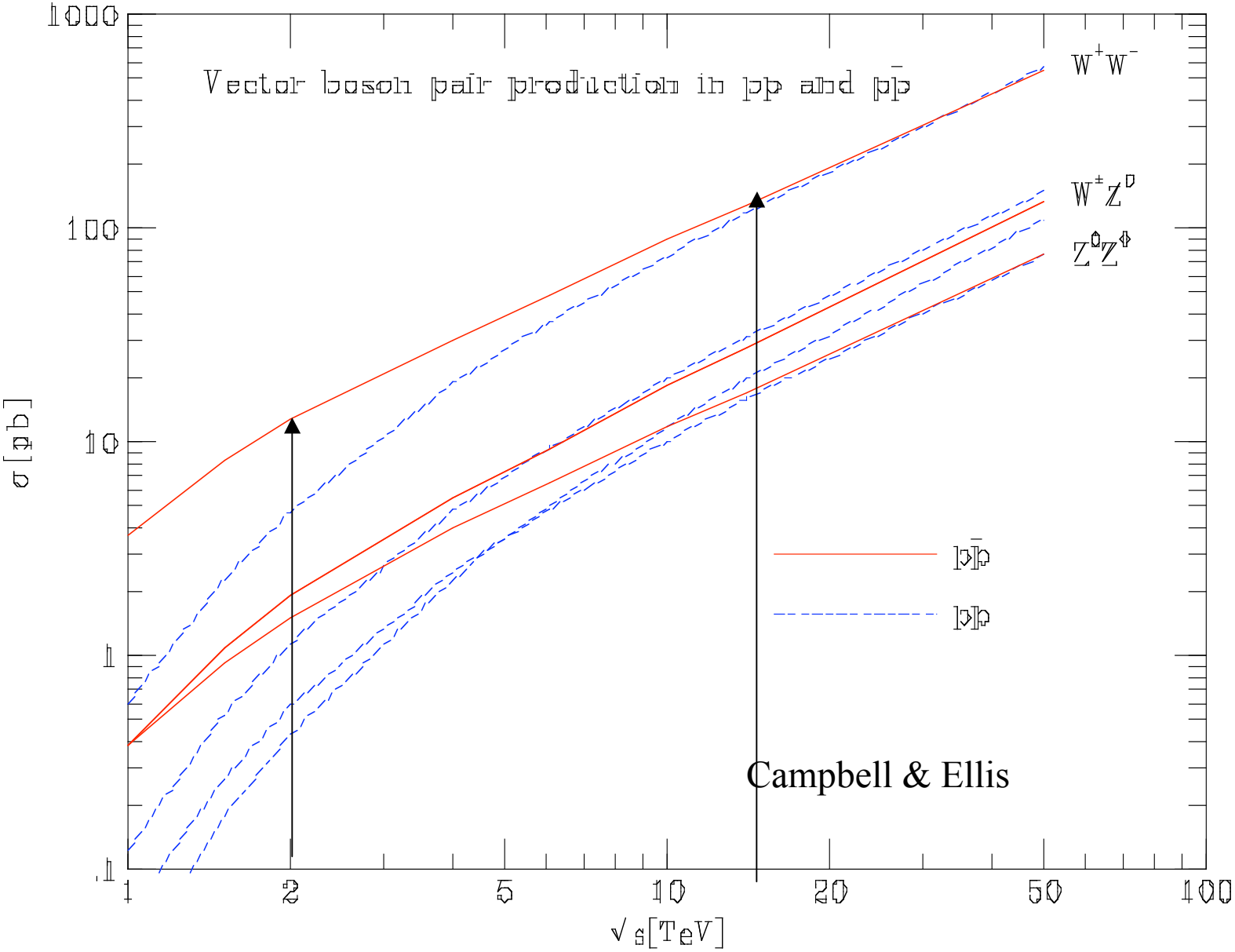


Backups

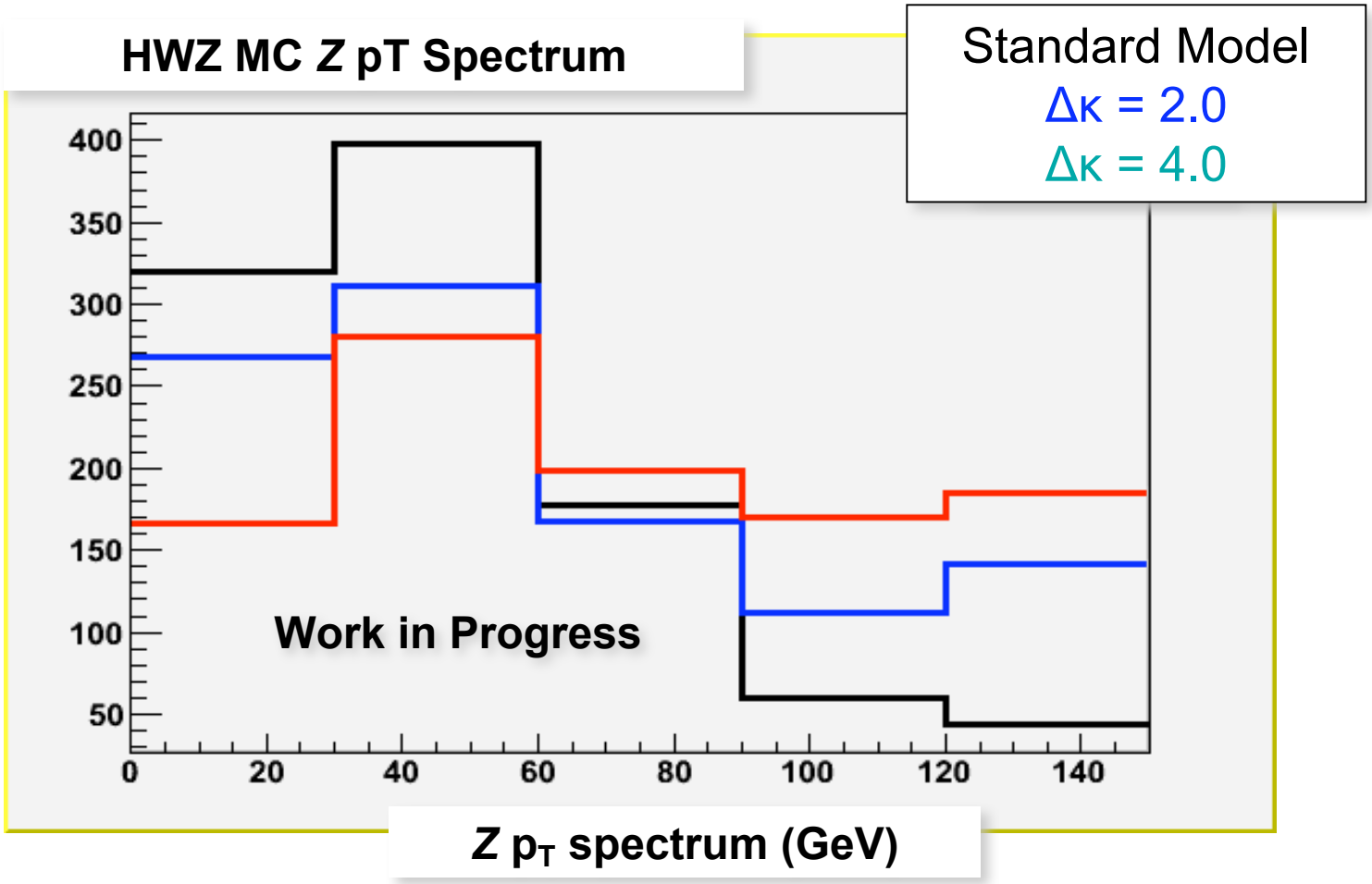
WZ Candidate



Diboson Cross Sections



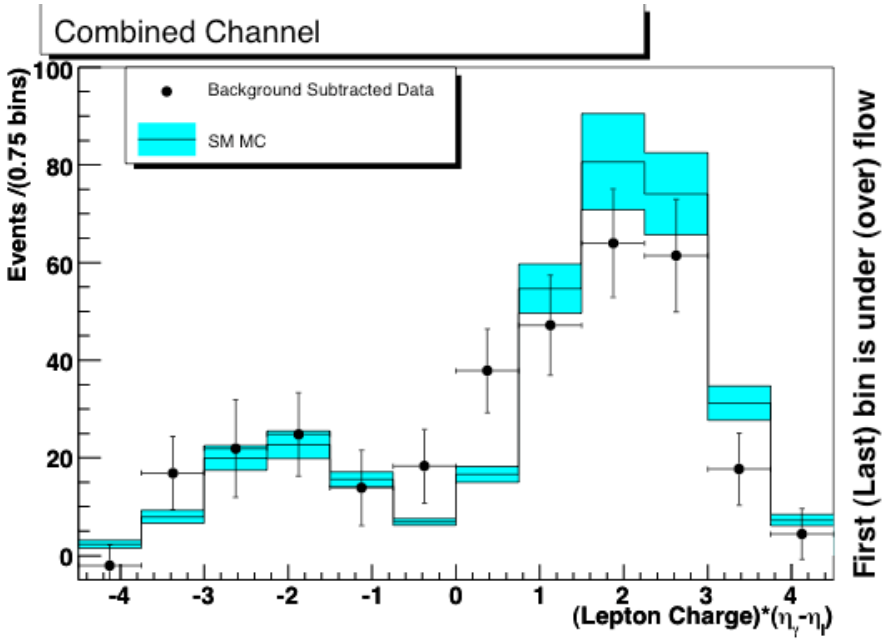
ZP_T Shape

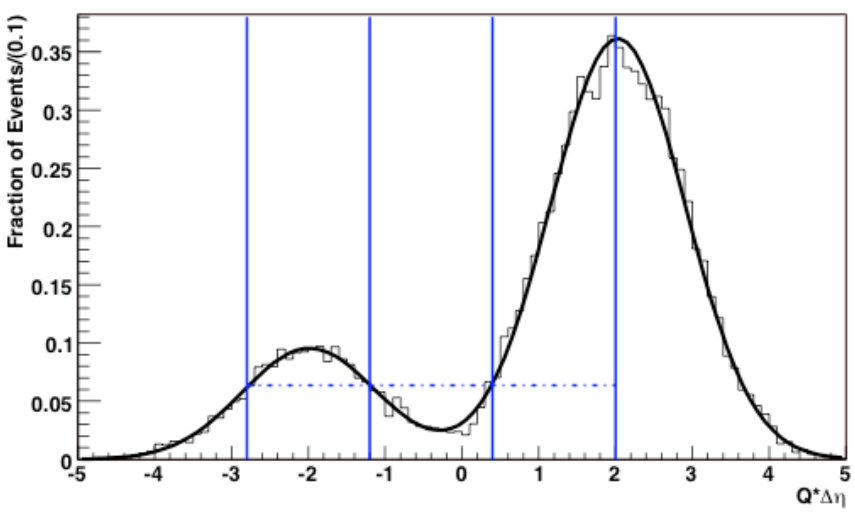

HWZ MC Z pT Spectrum
Standard Model
Δκ = 2.0
Δκ = 4.0
400
350
300
250
200
150
100
50
0
20
40
60
80
100
120
140
Work in Progress
Z pT spectrum (GeV)

$W\gamma$ Backgrounds

- W+jets events
  - Measured using the fake rate method
- Z+γ events
  - Scaled
- $W\gamma \rightarrow \tau\nu\gamma$
  - Scaled
- leX
  - W+e like events where the e is missing a track.
  - Scaled in data using tracking inefficiencies.

Dip Hunting

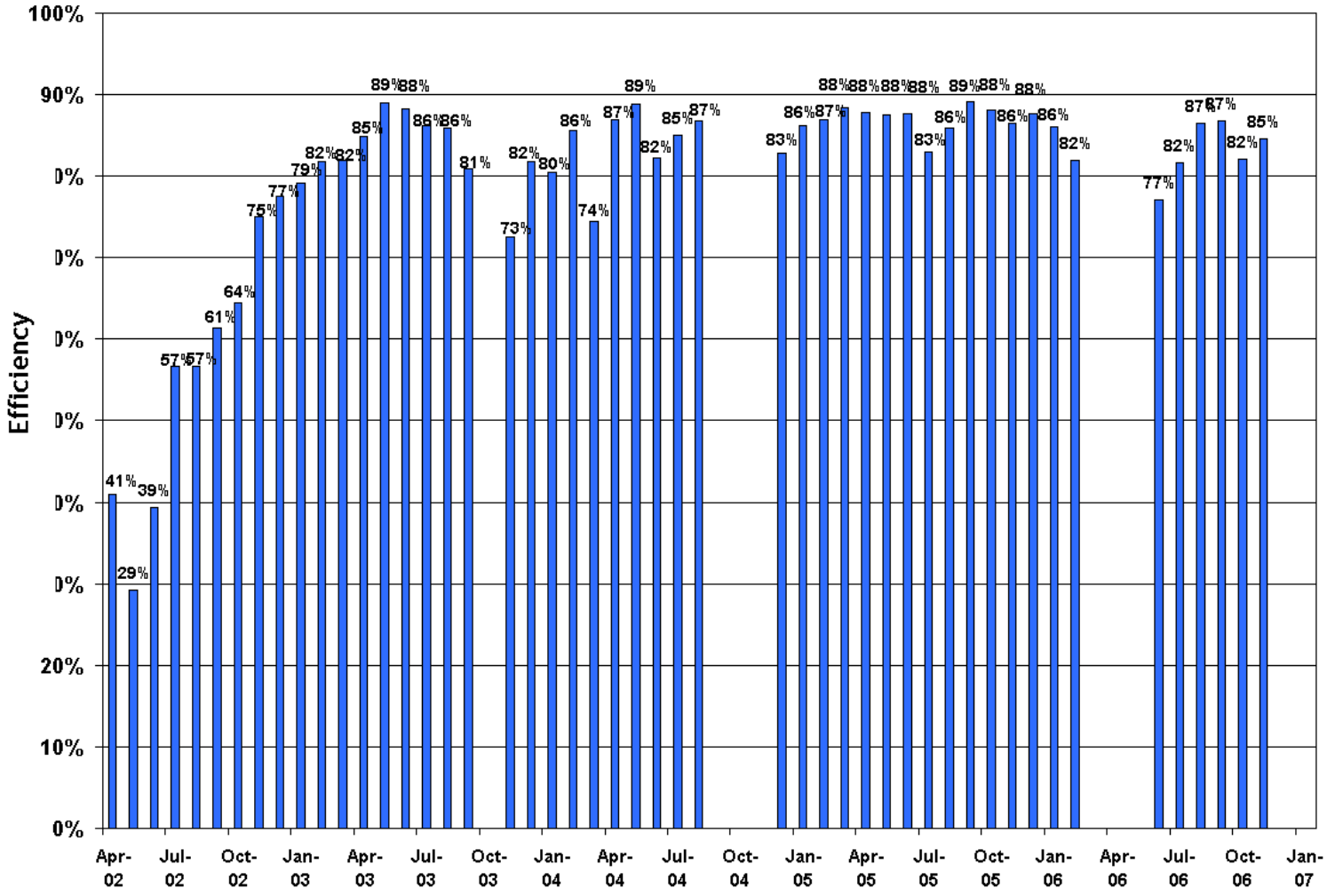




- Challenge is in how do you measure a zero, or “dip”.
- Unbinned methods
  - Look at shape of distribution and compare it to shapes with out dips
- Binned methods
  - Compare the number of events in dip region to the number of events in peak region.

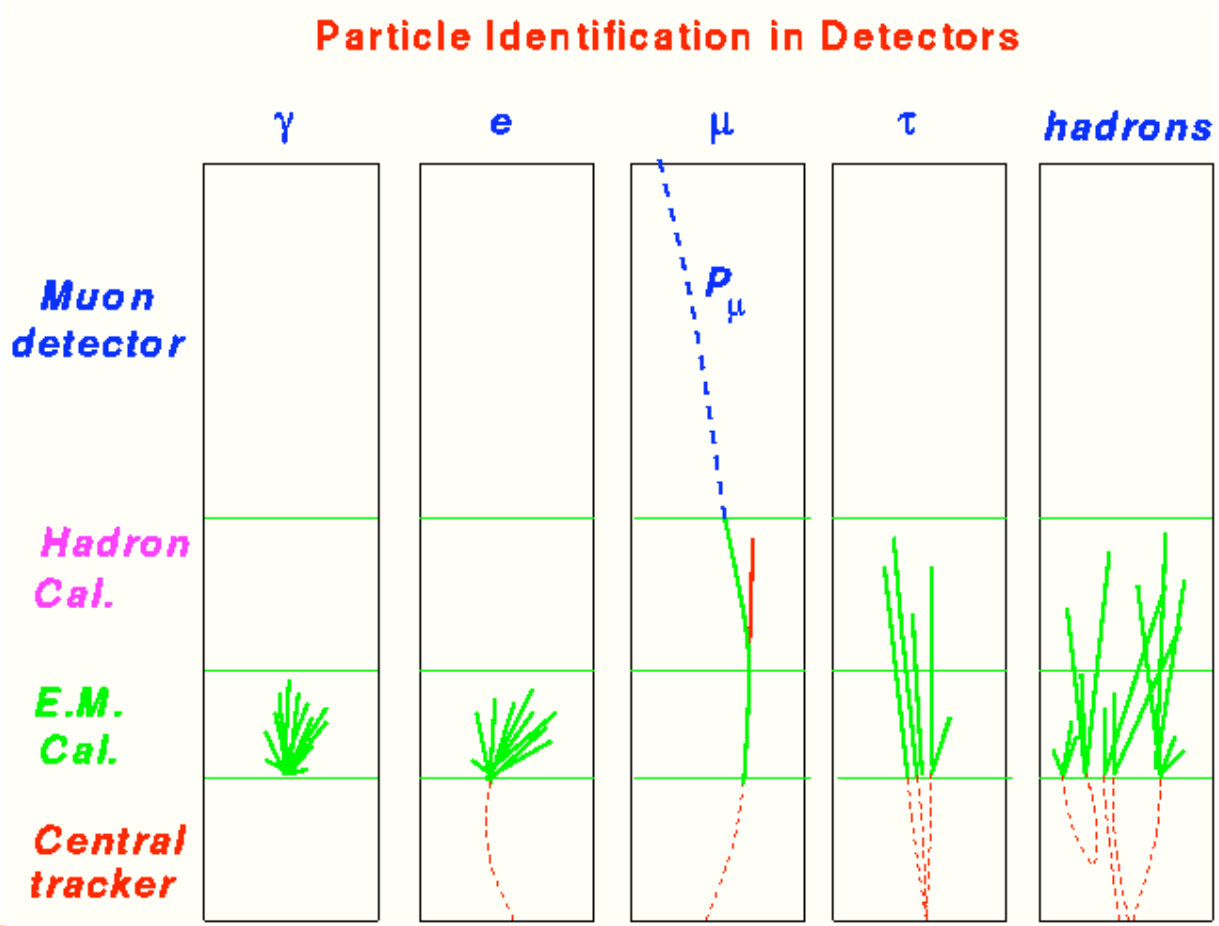
Monthly Data Taking Efficiency

19 April 2002 - 3 December 2006



Detector Objects

- What the detector really sees

- Electrons (e)
  - Trigger on Calorimeter.
  - Isolated.
  - Track.
  - Shower consistent with an e.

- Muons (μ)
  - Trigger on muon track.
  - Isolated.
  - Track.
  - Timing consistent with an ppbar crossing.