$WW \rightarrow \ell^- \bar{\nu} \ell^+ \nu$ Cross Section and Triple Gauge Couplings

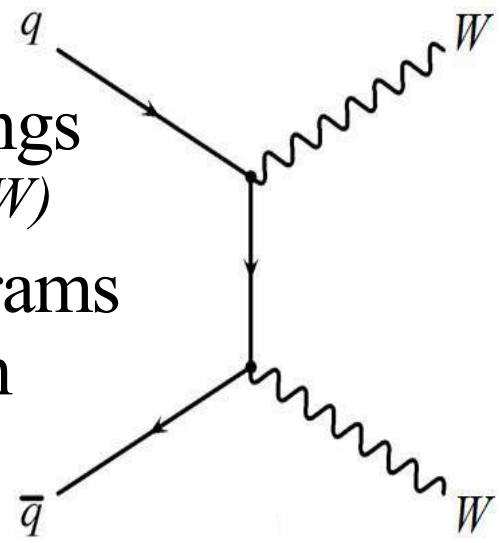
Michael Cooke

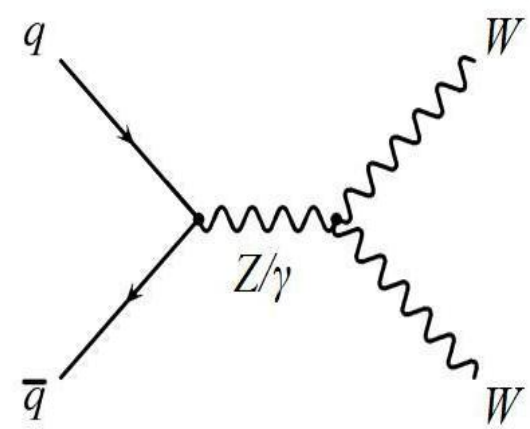
Overview

- Physical Motivation
  - Triple gauge couplings
- DØ Detector
  - Object definitions
- Data and Background Samples
- Signal Selection
  - Significance metric derivation
  - Channel selection optimization
- Cross Section Calculation
- Anomalous Coupling Study

Physics Motivation

- WW production is important to understand at Tevatron
  - Major background in the search for Higgs
  - Provides excellent opportunity to test the standard model
- The non-Abelian gauge-group structure of the EW portion of the SM predicts specific boson interactions
  - Two triple *(WWγ / WWZ)* and four quadruple couplings *(γγWW / ZγWW / ZZWW / WWWW)*
  - Interference between diagrams leads to finite cross section
  - Anomalous values of couplings would change behavior and indicate new physics!





Anomalous Triple Gauge Couplings

- Assuming EM gauge invariance and C and P conservation, the most general Lorentz invariant effective Lagrangian for triple gauge couplings is:

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

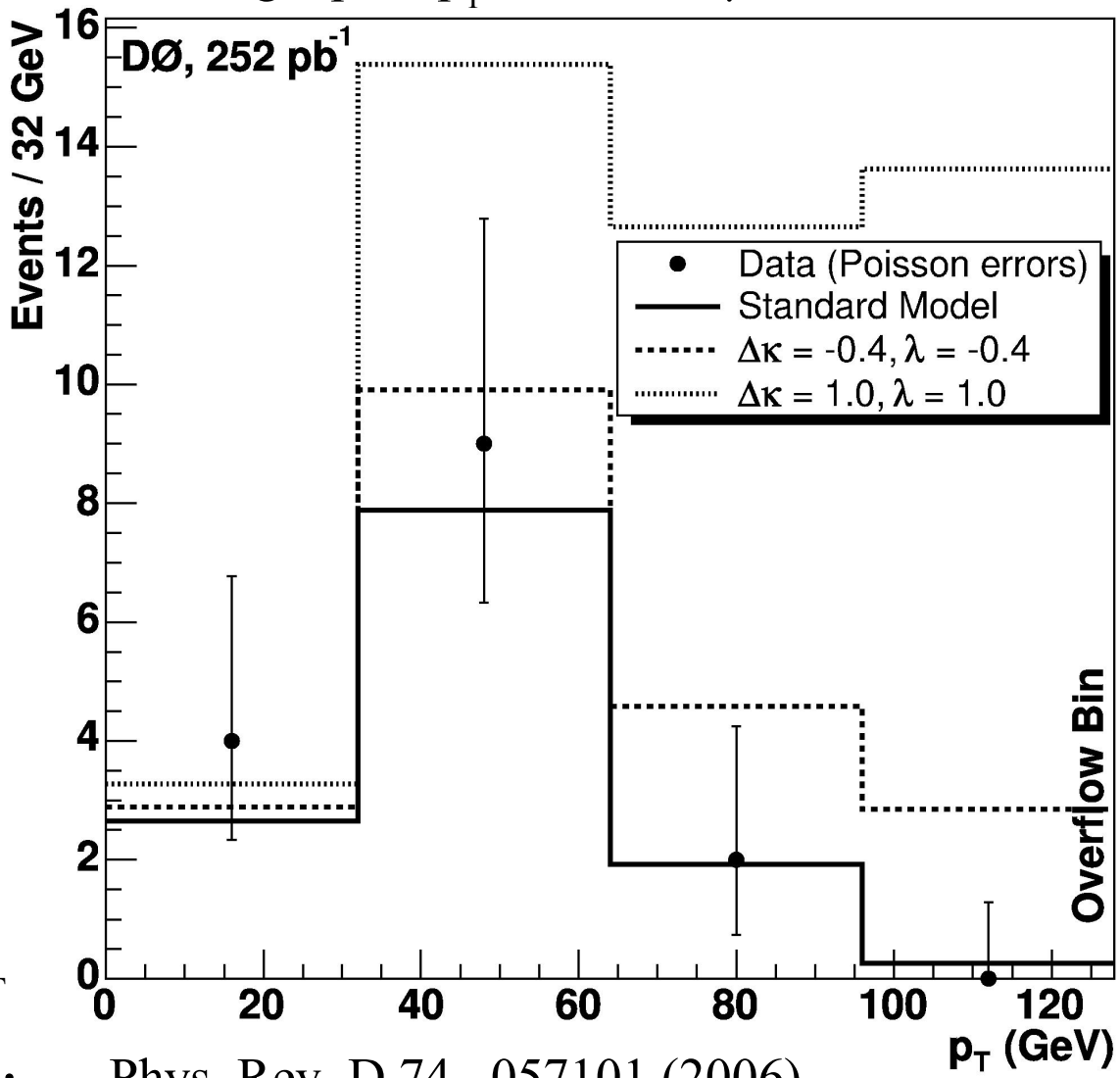
(where $V=\gamma$ or Z, $g_{WW\gamma} = -e$, $g_{WWZ} = -e\cot\theta_W$, and $\boxed{g_1^{\gamma} = 1}$)

- In the Standard Model, these triple gauge coupling parameters are fully constrained
  - In SM: $\lambda_Z = \lambda_\gamma = 0$, $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ ($\Delta\kappa_\gamma \equiv \kappa_\gamma - 1 = 0$)
- Can be considered corrections to W's magnetic dipole and electric quadrupole moments
  - Or their Weak counterparts...

Anomalous Triple Gauge Couplings

- Effects of anomalous couplings (AC):
  - Overall production cross section will increase
  - Kinematics of event changes
    - Higher p_T W's in CM
    - Angular distribution of W's in CM changes
  - In $WW \rightarrow \ell\nu\ell\nu$ events, only charged lepton p_T distribution available...

Leading lepton p_T in $WW \rightarrow e\mu$ events:



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Form Factor

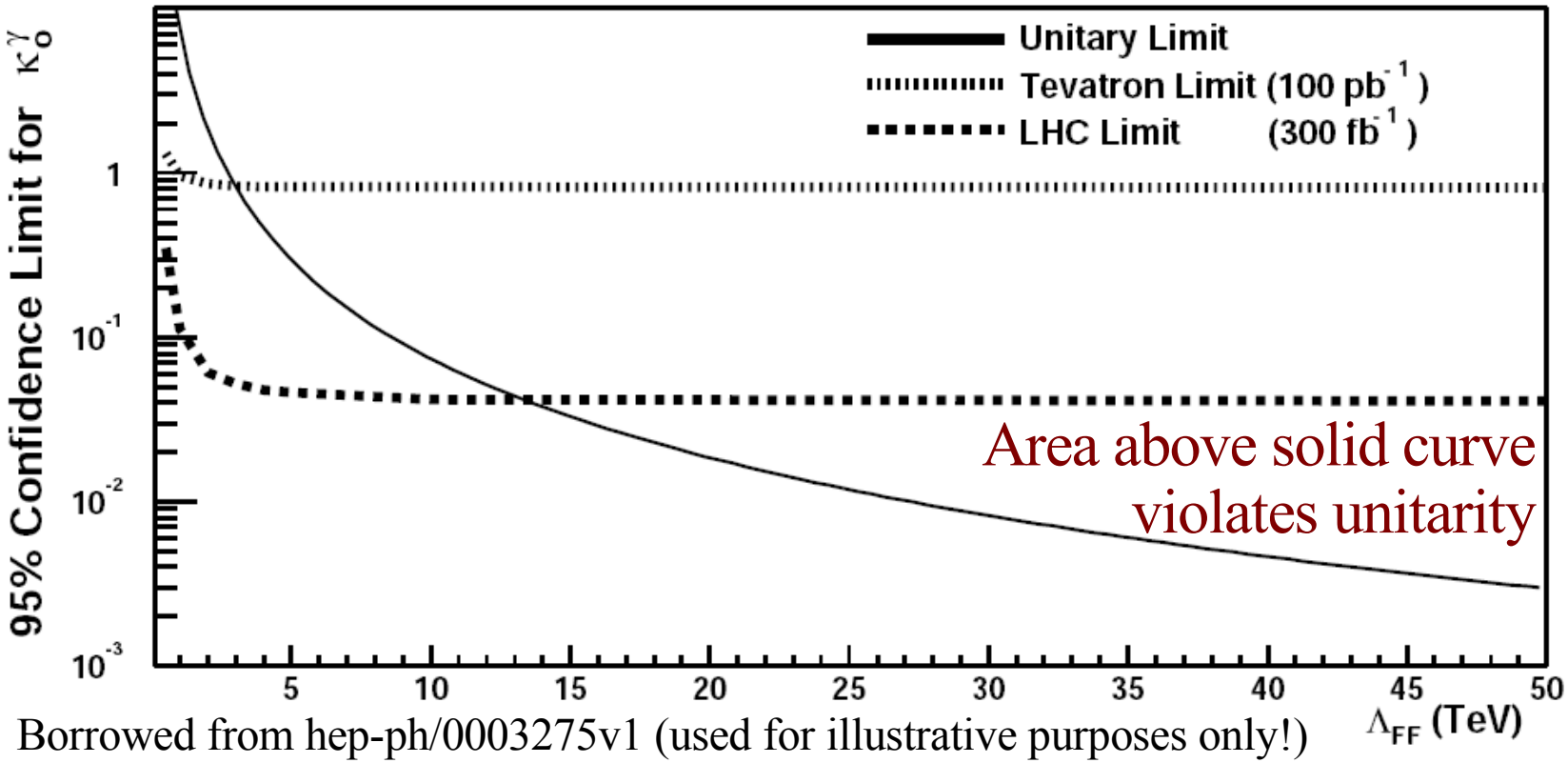
- The introduction of a single finite valued anomalous coupling will lead to unphysically large cross section!
  - $\Delta\kappa_V$ grows like $\sqrt{\hat{s}}$, λ_V and Δg_1^V grow like $\hat{s}$
  - Would like to consider model that is physically sensible at arbitrary energies, even if diboson production nearly on-shell
  - To conserve unitarity, a coupling, A, must be introduced as a form factor that vanishes as interaction energy increases:

$$A(\hat{s}) = \frac{A_0}{(1+\hat{s}/\Lambda^2)^2}$$

  - The form factor scale, Λ, is related to the energy at which new physics becomes important in electroweak physics

Unitarity Limits

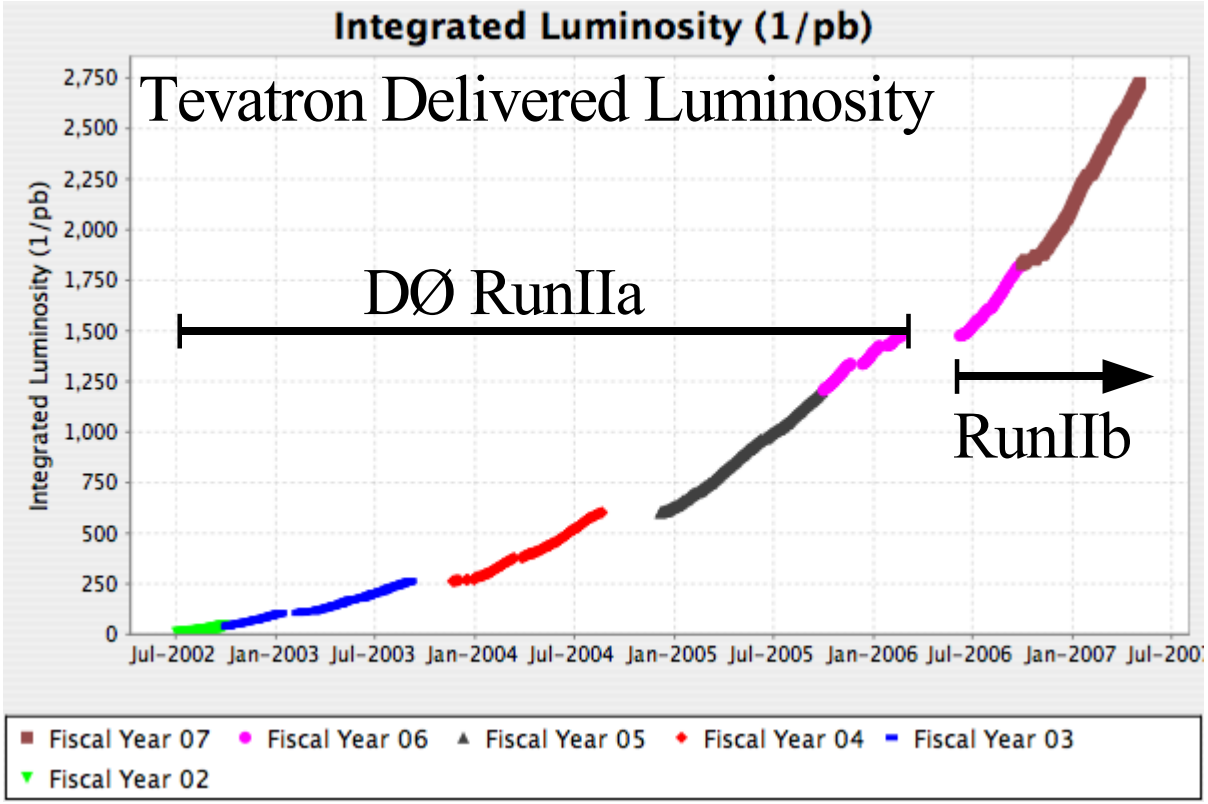
- Unitarity limit tightens as Λ increases, imposing effective limit on coupling values allowed
  - Machine energy (~2 TeV at Tevatron) is most sensible maximum value of Λ, if possible to reach...



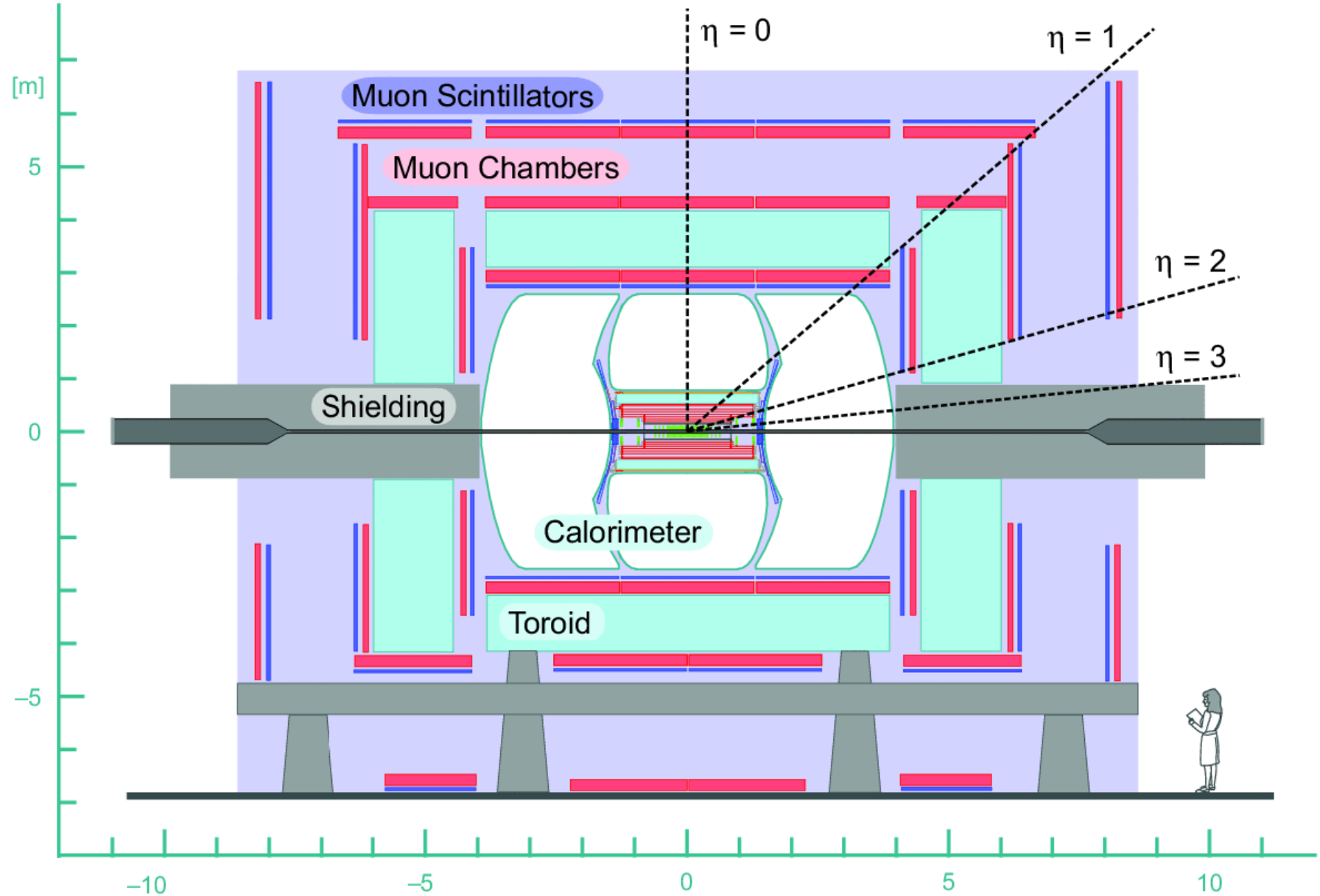
Borrowed from hep-ph/0003275v1 (used for illustrative purposes only!)

Data Sample

- Analysis uses full RunIIa data set
  - Data represents approximately 1 fb^{-1} of integrated luminosity
    - After detector dead time, trigger live time, and data quality checks...
  - Significant changes made to DØ during 2006 shutdown

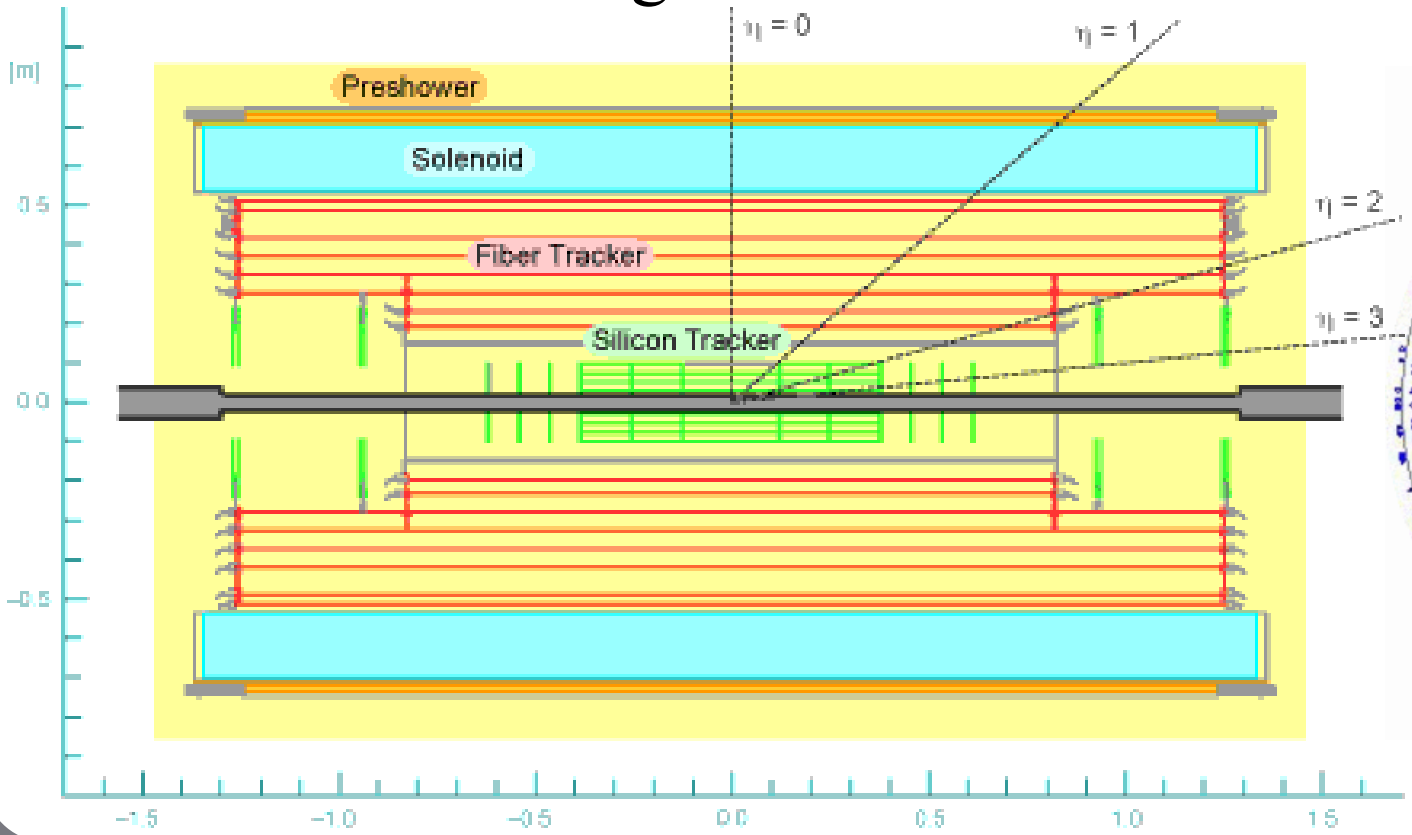


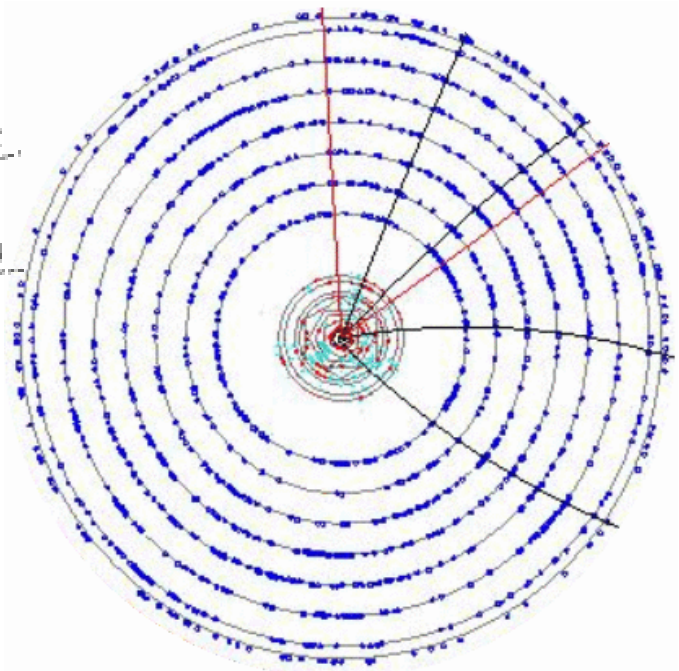
The DØ Collider Detector



The DØ Collider Detector

- Inner tracking volume of DØ detector
  - Silicon based tracking closest to interaction point (for accurate vertex positioning), surrounded by scintillating fiber tracker
  - Central tracking volume contained within 2 Tesla solenoid



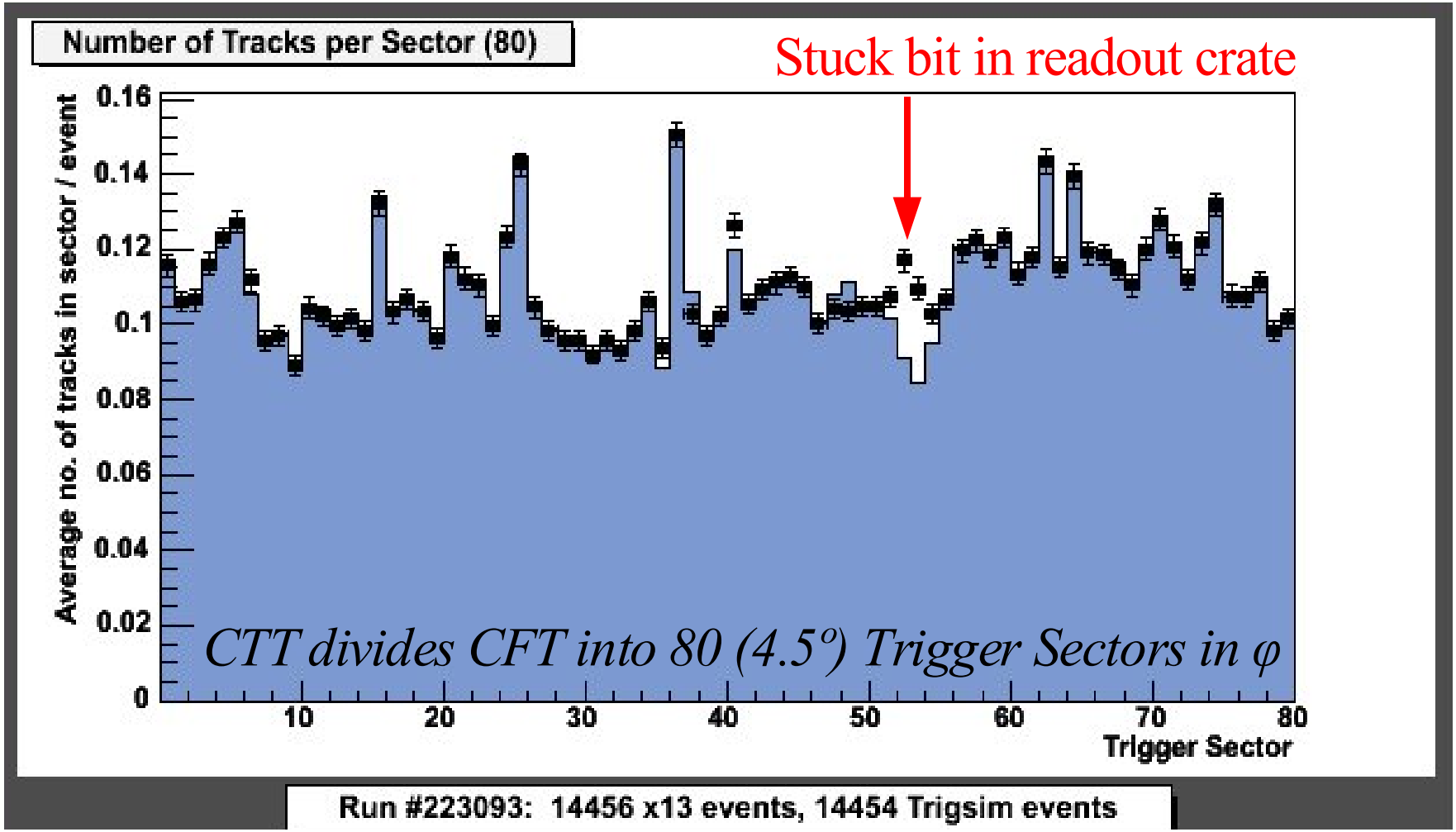


Detector Operations

- During normal operation, the Tevatron provides 1.7 million beam crossings per second!
  - Collisions occur 24/7, when possible, and collaborators monitor the DØ detector on a similar schedule
    - 24-hour on-call experts are required for all subdetectors
    - I was a Central Fiber Tracker expert (2003-2005)
  - Not all events can be written to tape!
    - We use a 3-tier triggering process to decide which events are worth keeping for analysis
  - Monitoring includes checking whether detector output from live events seem sensible
    - Programs that monitor live, streaming output are called "examines"
    - I wrote & maintained Central Track Trigger Examine (2002-2005)

Central Track Trigger Examine

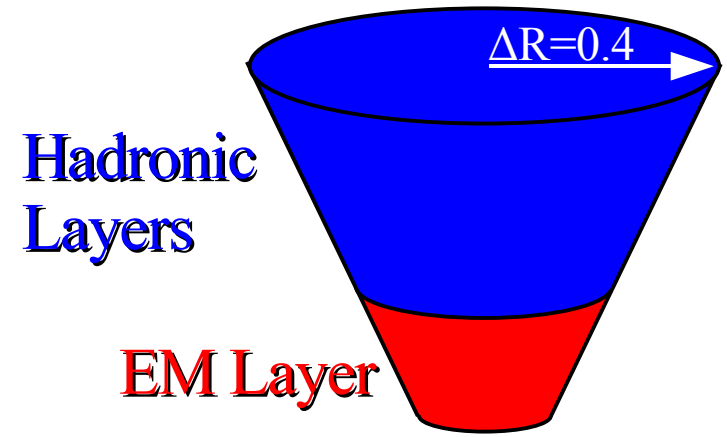
- Shows live comparison between CTT hardware output (dots) and trigger simulation prediction (histograms):



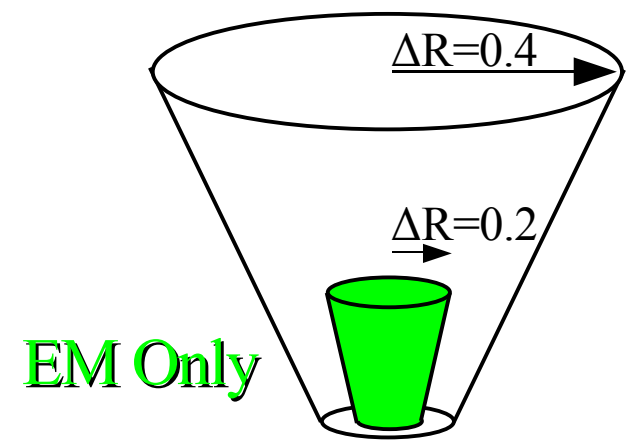
Object Definitions: Electron

Electron Definition

- Energy deposit in calorimeter with:
  - EM Fraction (■ / [■+■]) > 0.9
  - Isolation (□ / ■) < 0.2
- Must be in fiducial region of calorimeter
  - Gap in full EM layer coverage between movable & central sections of calorimeter
- Track match from central tracking
- Tight cut on multivariate electron discriminator
  - Input variables include track quality, shower shape, E_T/p_T, isolation



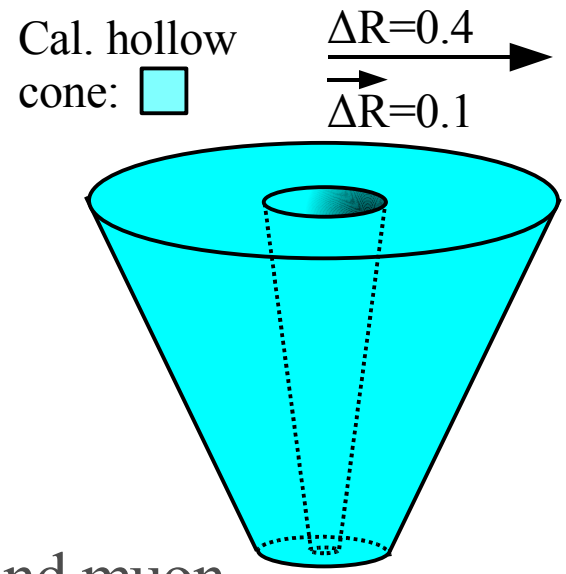
$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$$



Object Definitions: Muon

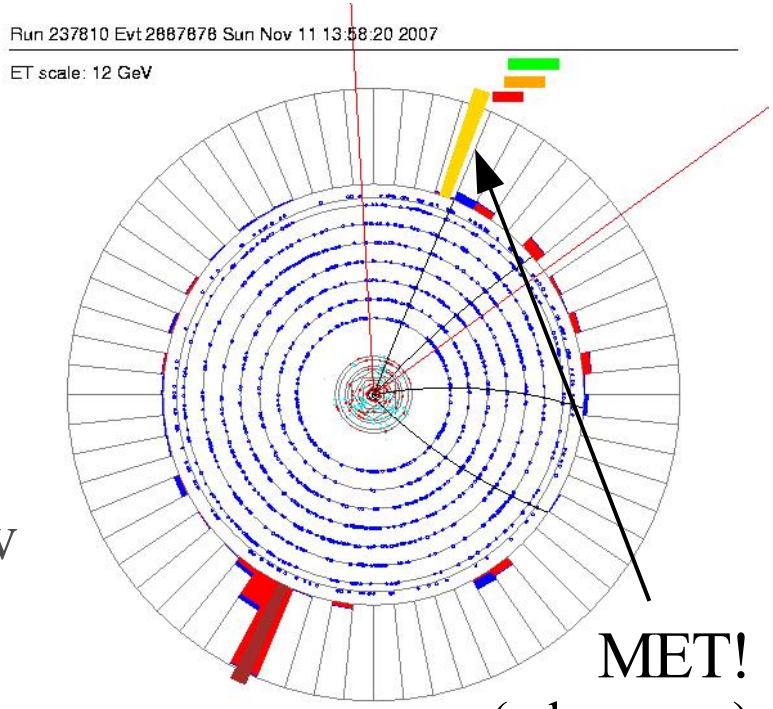
Muon Definition

- Muon system layer activity on both sides of toroid
  - Must have matched wire and scintillator hits on each side of toroid
    - Suppresses fakes from calorimeter punch through into first muon layer
  - Single layer hit acceptable where support structure limits coverage
  - Veto cosmics with scintillator timing cut
- Match to track from central tracking
  - Better p_T resolution from central tracks
    - Using SMT or beamspot for accurate measurement
  - Veto cosmics with track DCA cut
- Tight isolation required
  - Veto on high sum of other track p_T in cone around muon
  - Veto on too much calorimeter E_T in hollow cone around muon



Object Definitions: Neutrino?

- Neutrinos will not directly appear in the DØ detector
  - Not impossible, but so improbable that we assume this case!
- However, we tend to see most other high p_T particles!
  - The vector sum of all particle p_T in an event is zero
  - We add up everything in the calorimeter and determine the missing transverse energy vector
  - This gives us a measure of the sum of the E_T of neutrinos in an event
    - No E_Z information, since we don't know total E of event's parton collision
  - Must carefully correct for muons!



MET!
(...here, a μ)

ee, eμ, μμ Channel Preselection

- Two charged lepton objects found in an event
- $p_{T,Lead} > 25$ GeV, $p_{T,Trail} > 15$ GeV
- $\Delta R(\ell_{Lead},\ell_{Trail}) > 0.8$ (ee), > 0.5 (eμ, μμ)
  - This keeps the calorimeter isolation cones from overlapping
- Tracks must have a z-position within 2 cm of the primary vertex
  - Missing E_T is calculated with respect to the primary vertex!
- Leptons have opposite charge sign
- Lepton fires single electron (ee, eμ) or muon (μμ) trigger
- ee: At least one electron within the central calorimeter

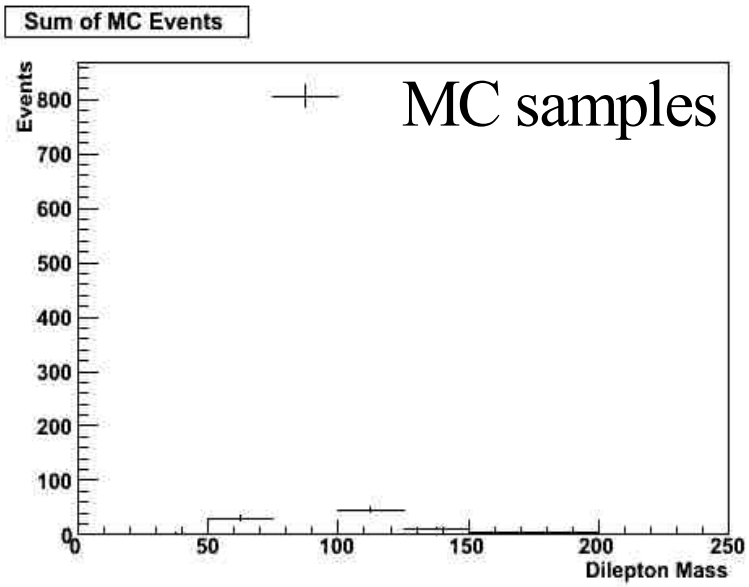
Monte Carlo Samples

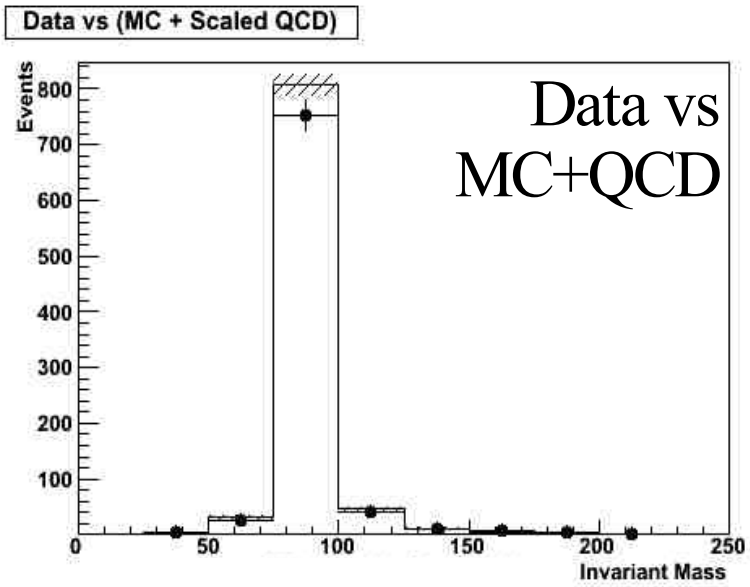
- Signal and most backgrounds are modeled by MC
  - Except for dijet QCD, which is estimated from data samples...
- MC samples are generated by Pythia and run through a GEANT based full detector simulation
  - This output is further corrected as needed to reflect the behavior of the DØ detector
    - Muon resolution correction
    - Charge mis-id correction
    - Selection efficiencies
    - Trigger efficiencies
  - Samples are luminosity weighted based on their theoretical cross sections

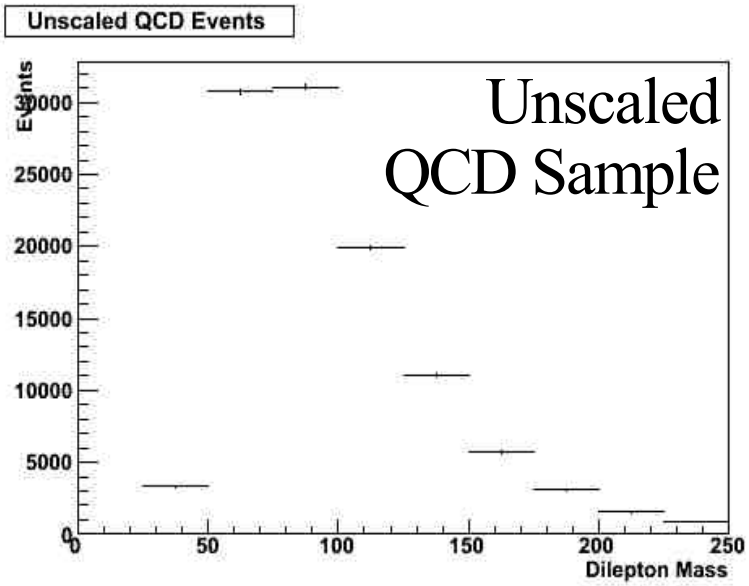
QCD Estimation

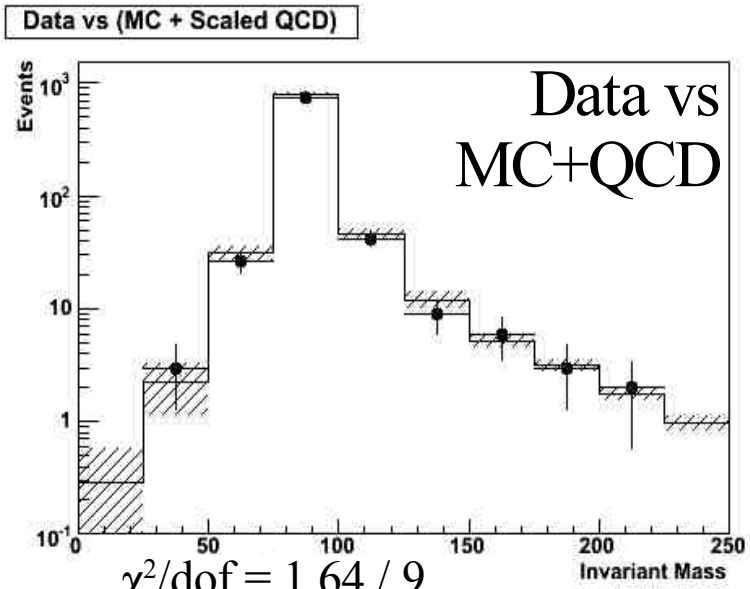
- A "bad lepton pair" sample is picked for each channel to provide the shape of the QCD background
  - Bad electrons fail the multivariate discriminator cut
  - Bad muons fail the calorimeter isolation cut
- The QCD sample is fit to the data same-sign lepton invariant mass spectrum in each channel
  - Channels divided into electron central/endcap topologies
  - All MC samples are fixed to luminosity normalized amount
  - QCD is forced to make up (Data – MC) difference
    - Dilepton mass spectrum fit to minimize χ^2 value
- This is done once, after preselection, for each channel
  - QCD scale factor is fixed for remainder of analysis

QCD Estimation (ee CC-EC events)



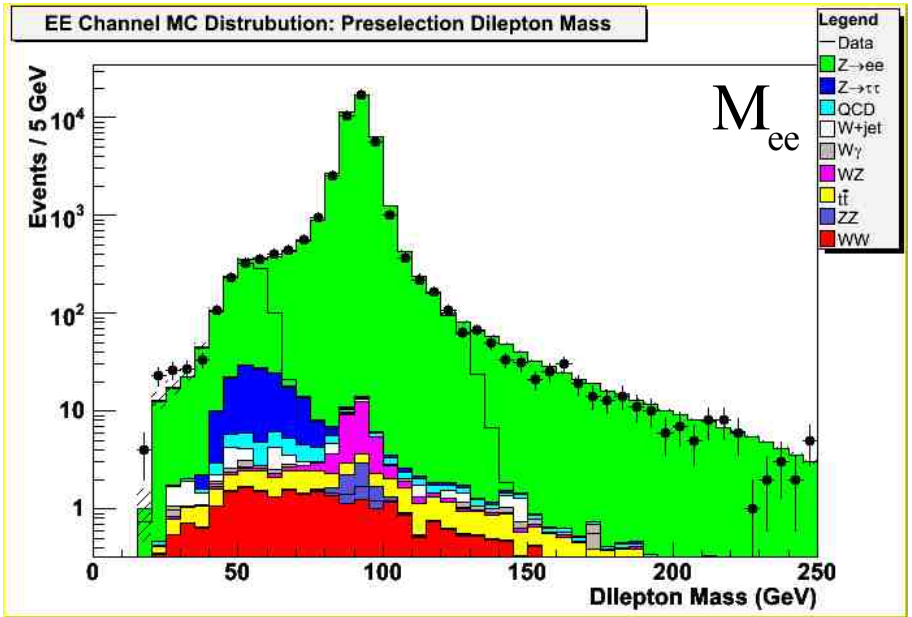


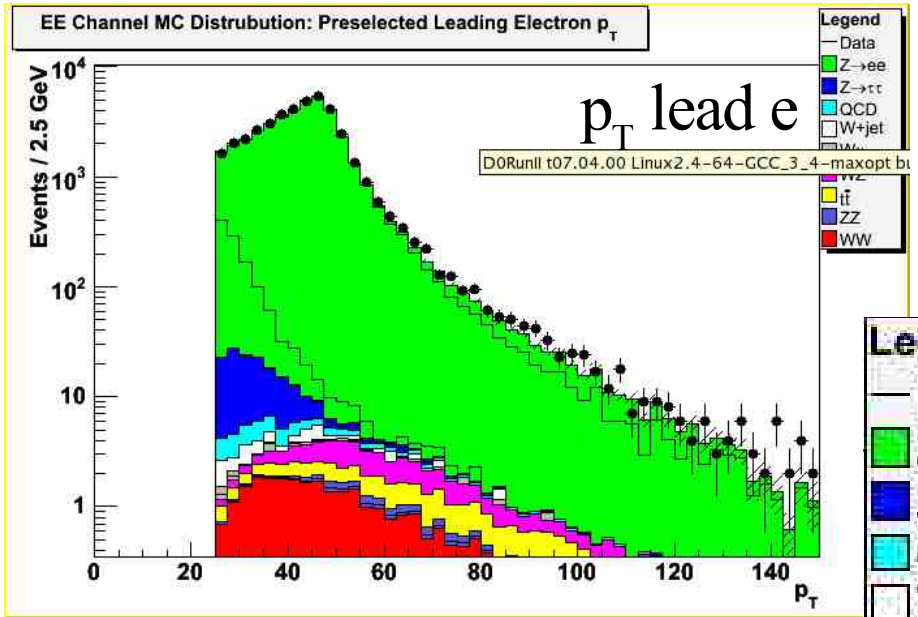


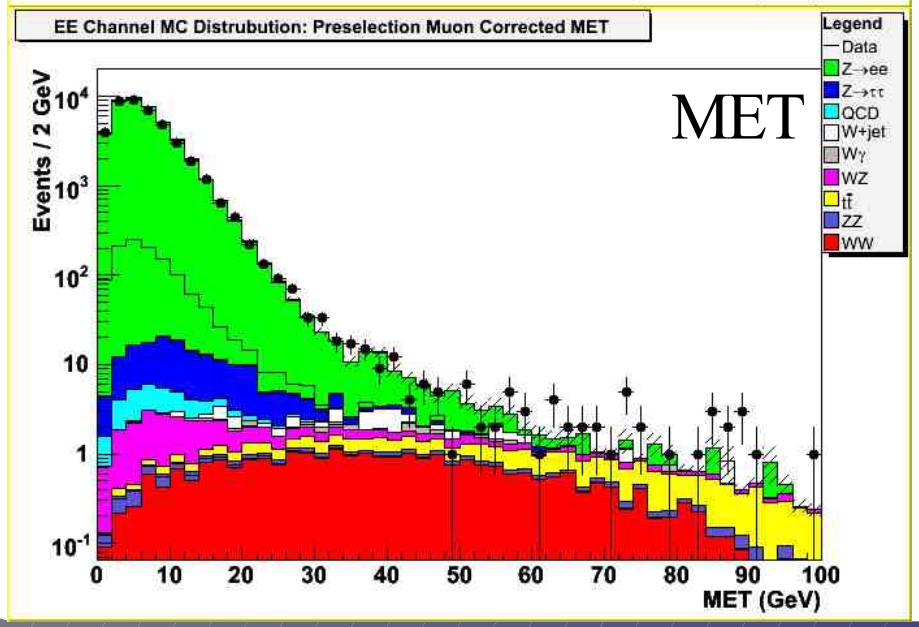


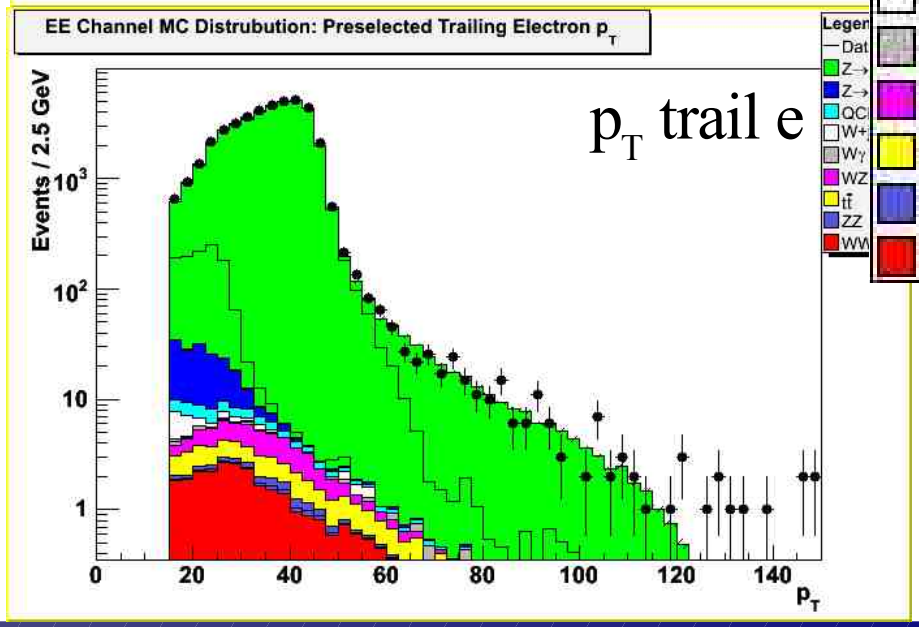
$\chi^2/\text{dof} = 1.64 / 9$

Preselected Distributions (ee)

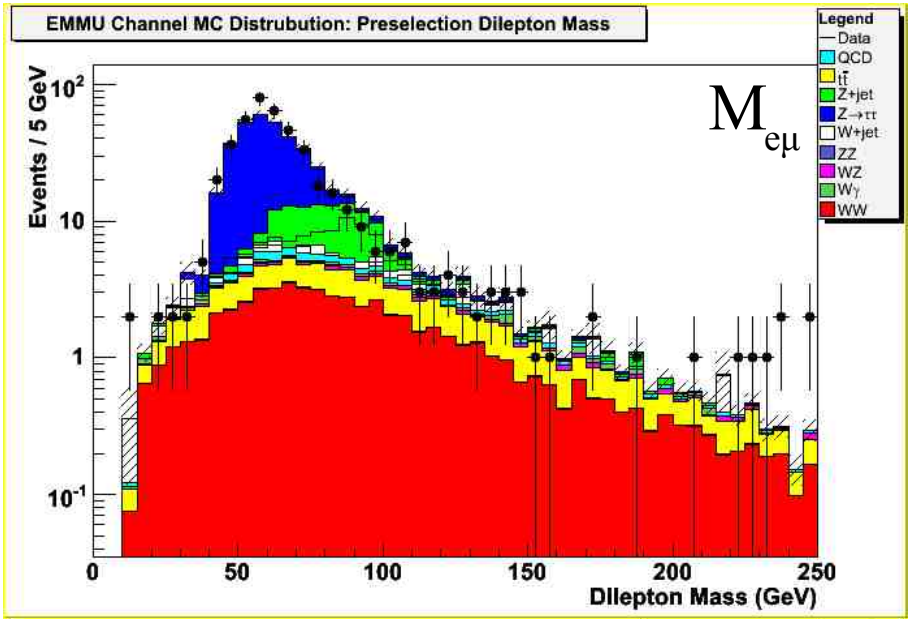


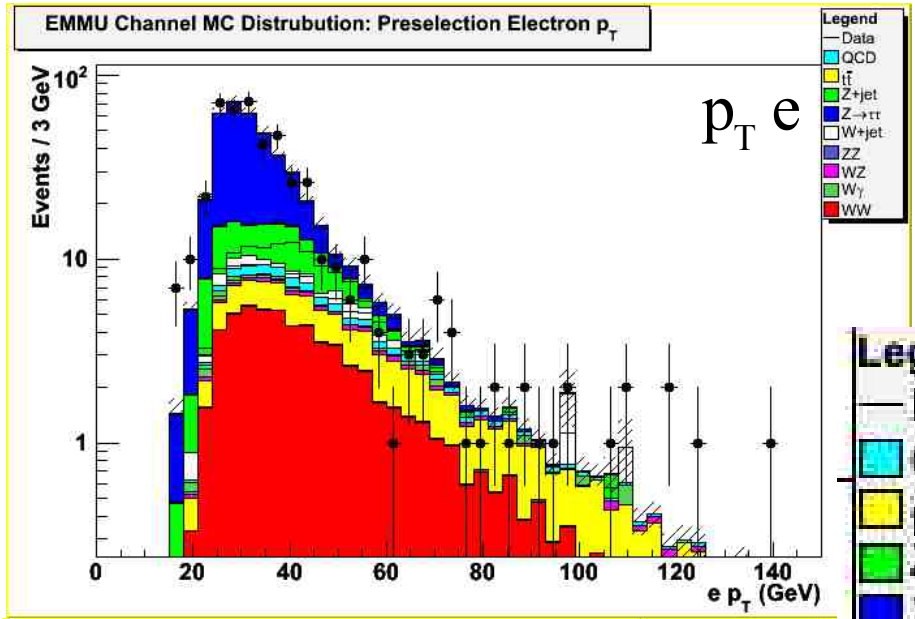


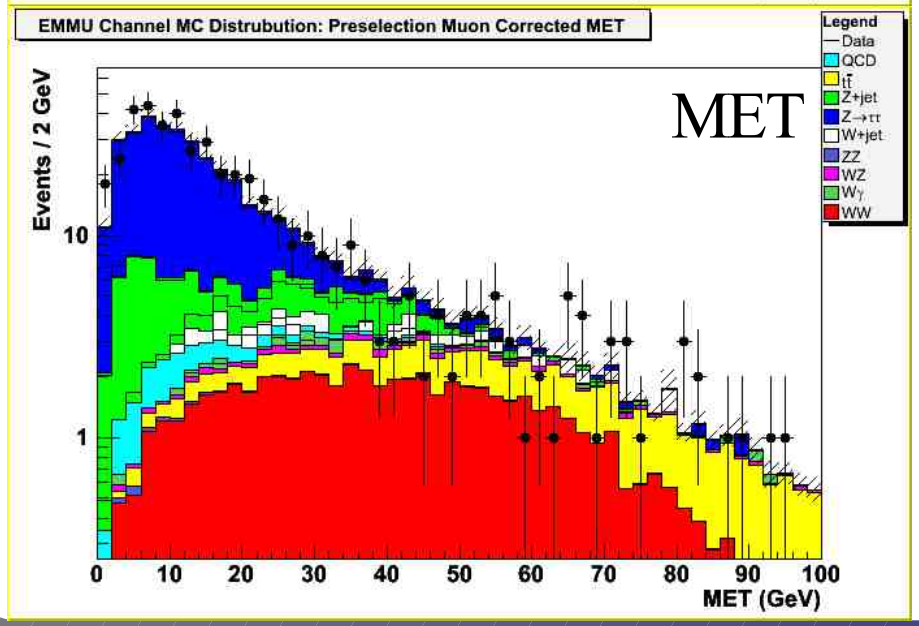


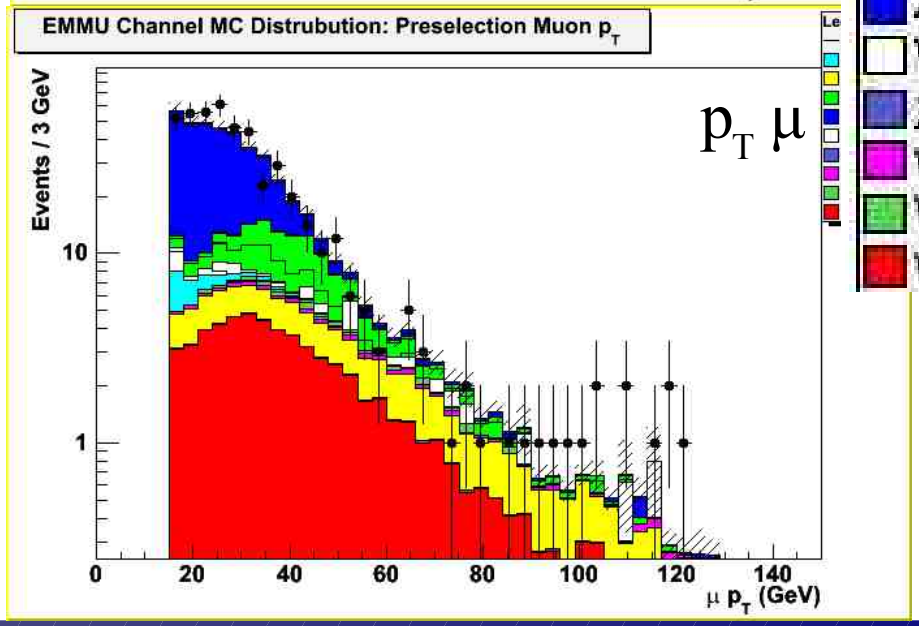


Preselected Distributions (eμ)

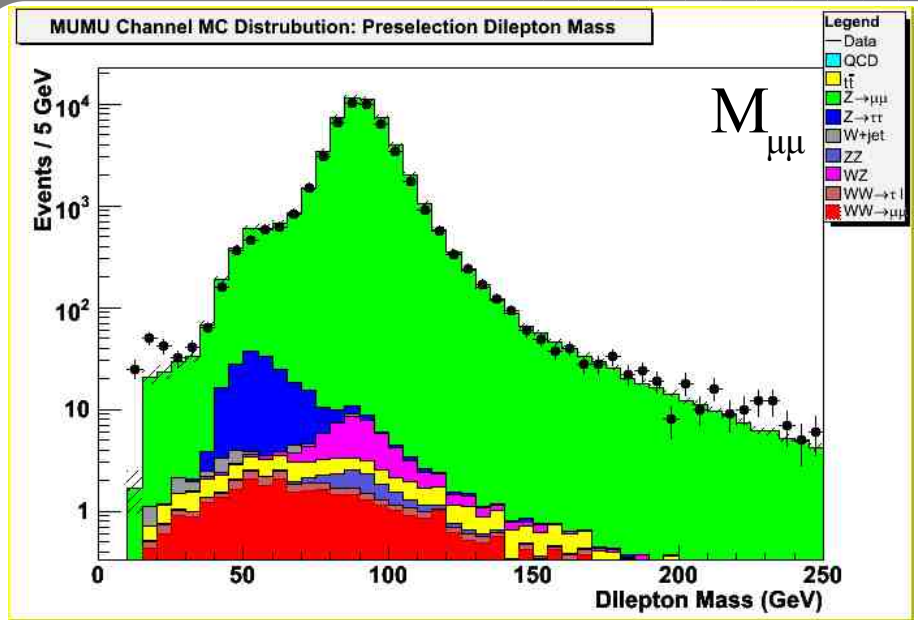


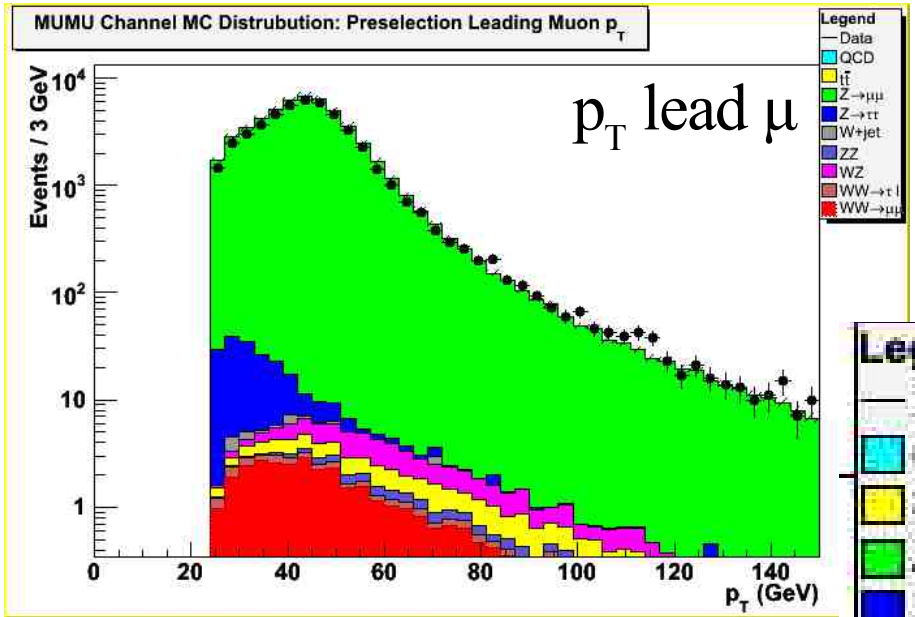


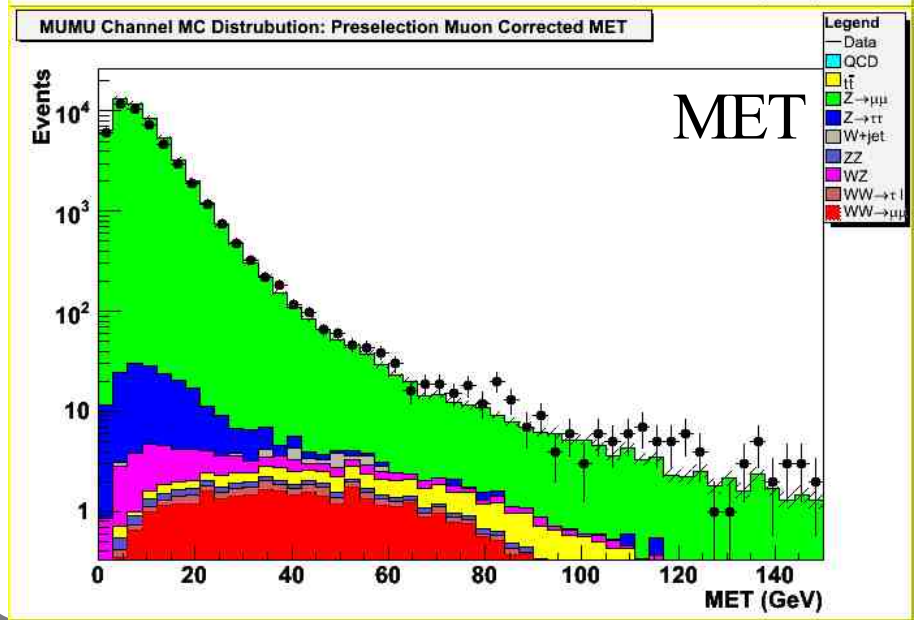


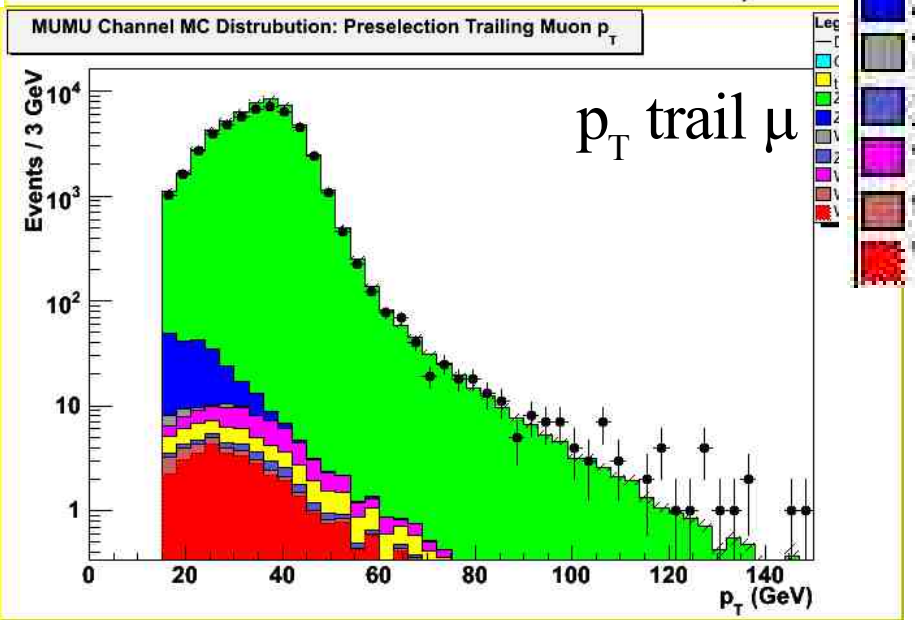


Preselected Distributions (μμ)









Selection Cut Optimization

- Considering the cross section equation $LA\epsilon\sigma = N - B$, the uncertainty on the cross section, δ_σ, is:

$$\delta_\sigma^2 = \frac{1}{(LA\epsilon)^2}\left(\delta_N^2 + \delta_B^2 + (N-B)^2\frac{\delta_L^2}{L^2} + \ldots\right)$$

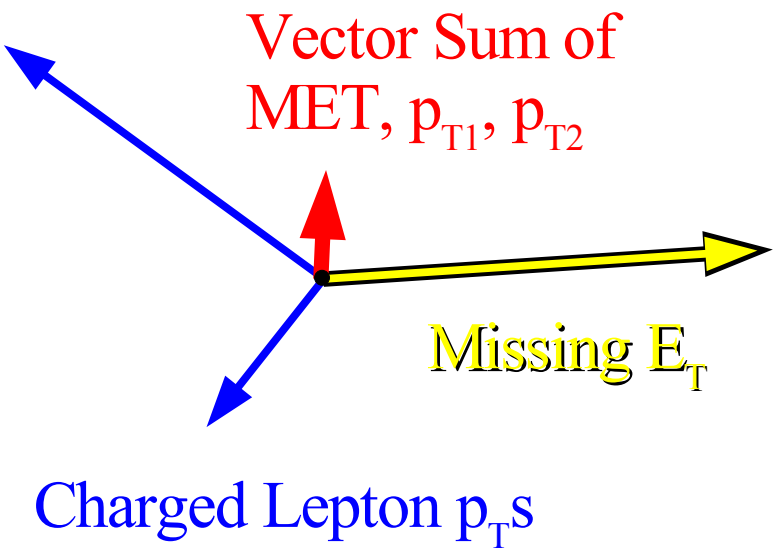
- If $\delta_N = \sqrt{N}$, then the quantity to maximize is:

$$\frac{\sigma}{\delta_\sigma} = \frac{N-B}{\sqrt{N + \delta_B^2 + (N-B)^2\delta_L^2/L^2 + \ldots}} = \frac{S}{\sqrt{S + B(+\ldots)}}$$

- Each channel (ee, eμ, μμ) uses this metric in order to find the optimal set of selection cuts based on MC

Signal Selection

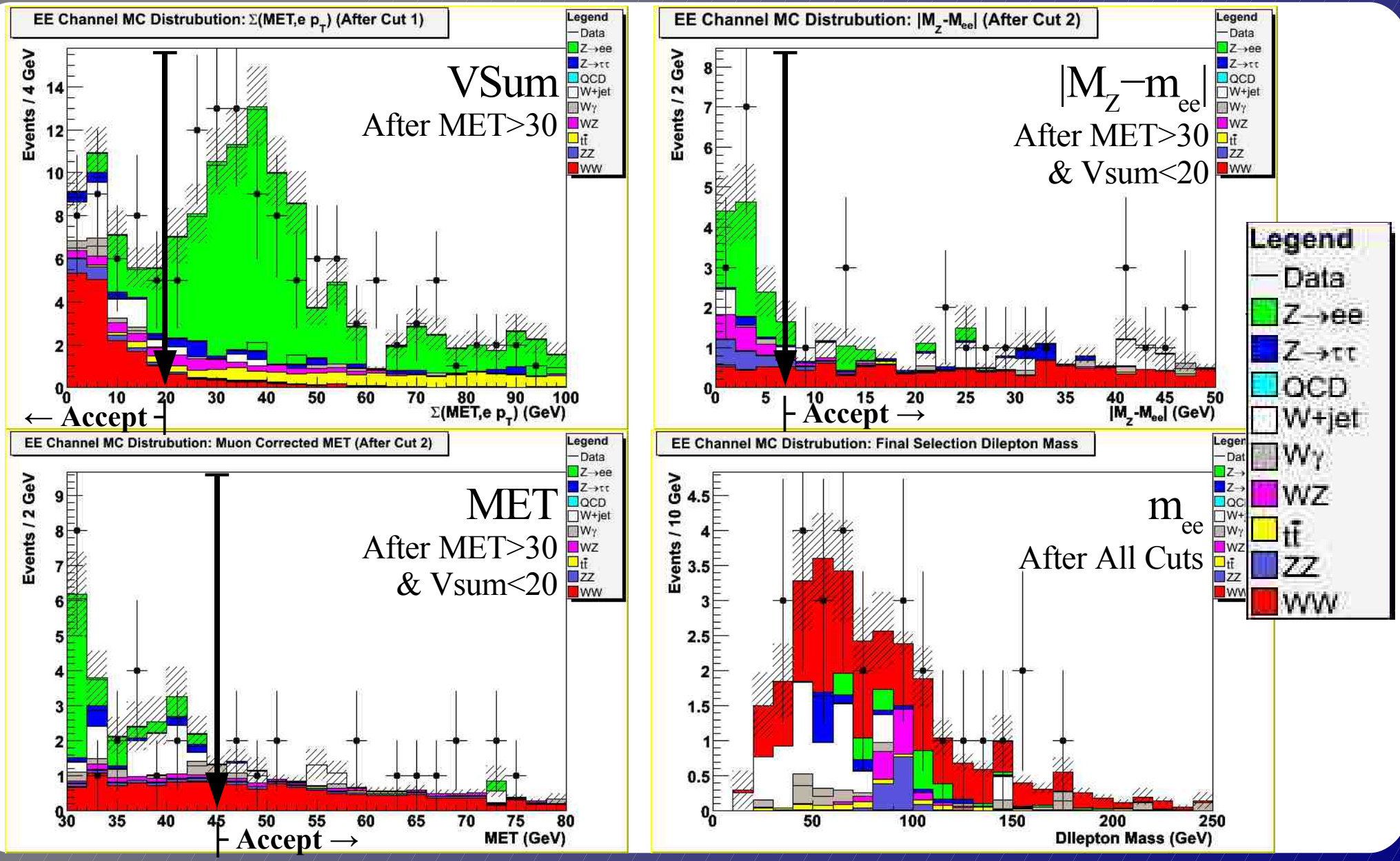
- These cuts were found to give the highest $S/\sqrt{S+B}$ when used to discriminate signal from background:
  - Missing E_T (muon corrected)
  - Vector sum of Missing E_T and both lepton p_Ts
  - ee: Z-mass window cut used with additional MET selection
    - Keep events in Z-mass window when MET above a higher threshold
  - eμ, μμ: $\Delta\varphi_{\ell\ell}$ cut, possibly used with additional MET selection
    - Keep events with high $\Delta\varphi_{\ell\ell}$ when MET above a higher threshold
  - μμ: Acollinearity cut between μ and MET ($\cos\theta < 0.98$)



ee Signal Selection

- Significance optimization led to this set of cuts:
  - Cut 1: MET > 30 GeV
  - Cut 2: Vector sum of MET, e p_Ts < 20 GeV
  - Cut 3: MET > 45 GeV when $|M_Z - m_{ee}| < 7$ GeV
- Final selection cuts yield...
  - Errors reflect (stat + efficiency + charge mis-id) only!
  - Expected WW signal: 14.47 ± 0.54 events
  - Expected Σ backgrounds: 14.72 ± 1.69 events
  - Expected significance: 2.92 (including lumi uncertainty)
  - Expected total: 29.20 ± 1.78 events
  - Candidate events in data: 29 (observed significance 2.92)

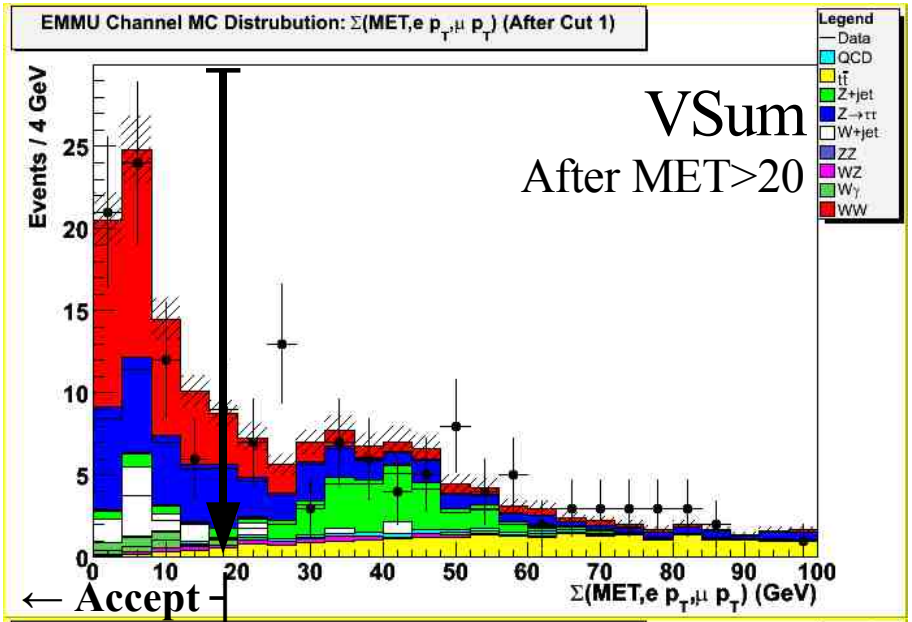
ee Signal Selection Plots

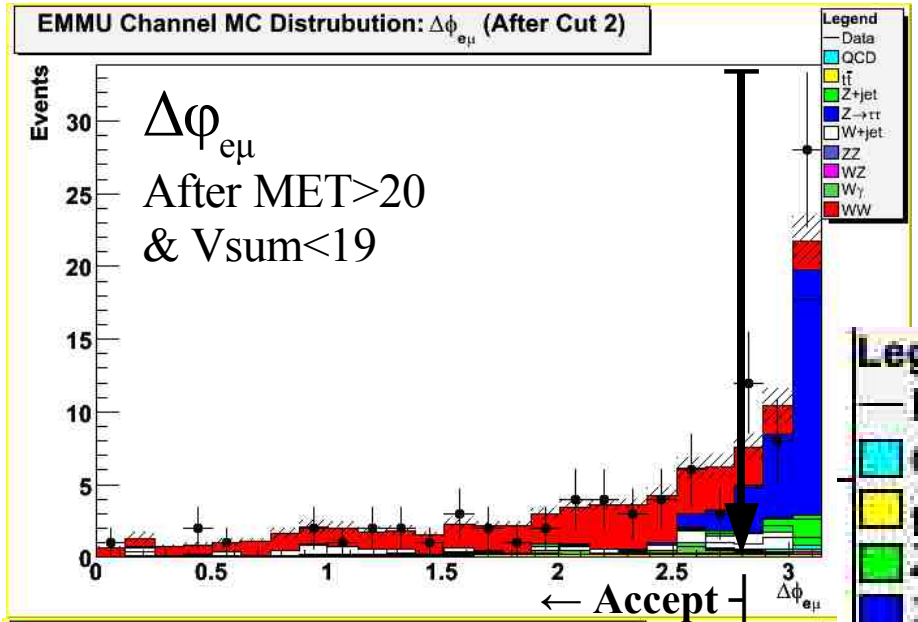


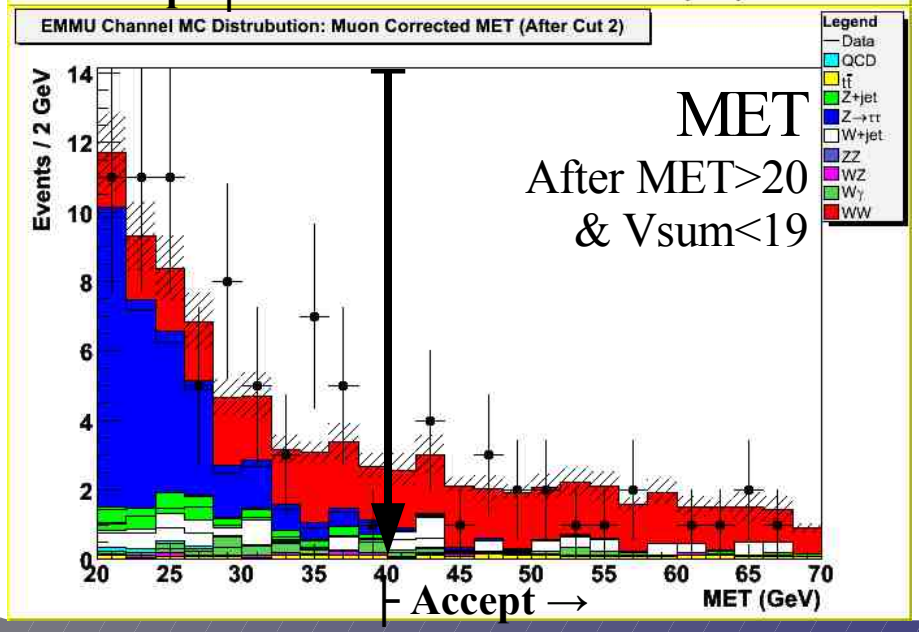
eμ Signal Selection

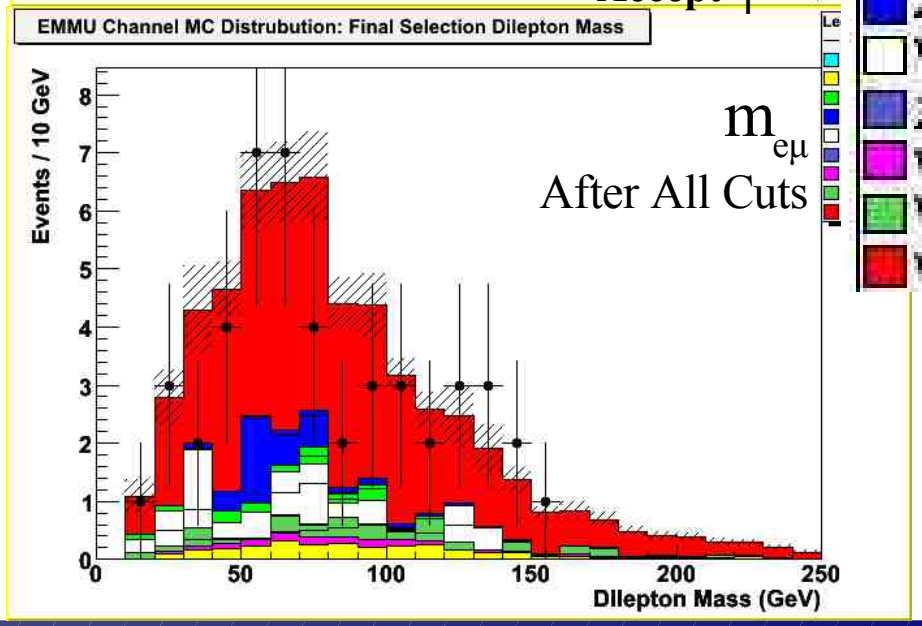
- Significance optimization led to this set of cuts:
  - Cut 1: MET > 20 GeV
  - Cut 2: Vector sum of MET, e p_T, μ p_T < 19 GeV
  - Cut 3: MET > 40 GeV when $\Delta\varphi_{e\mu} > 2.8$
- Final selection cuts yield...
  - Errors reflect (stat + efficiency + charge mis-id) only!
  - Expected WW signal: 39.00 ± 0.66 events
  - Expected Σ backgrounds: 19.18 ± 1.76 events
  - Expected significance: 6.43 (including lumi uncertainty)
  - Expected total: 58.18 ± 1.91 events
  - Candidate events in data: 48 (observed significance 4.99)

eμ Signal Selection Plots





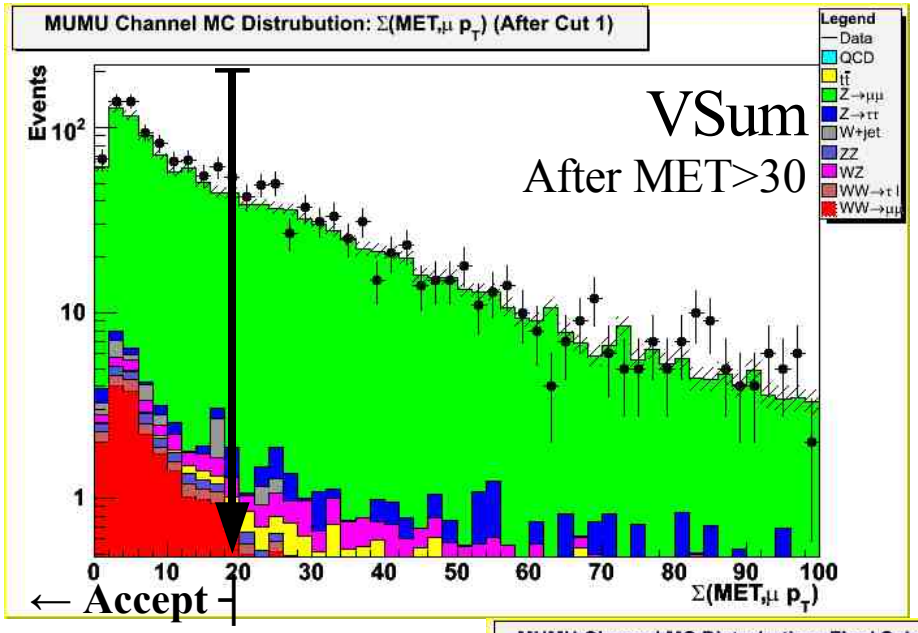


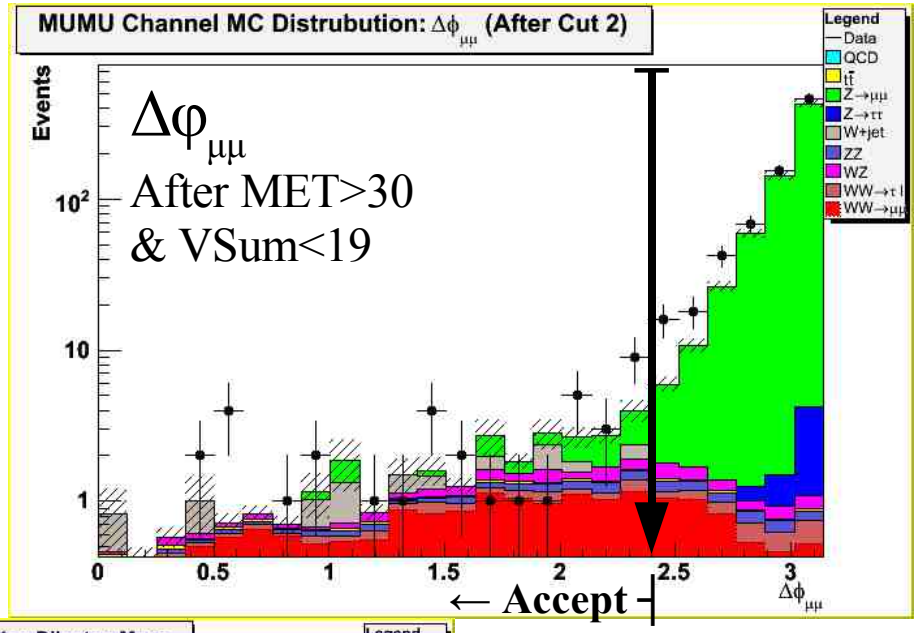


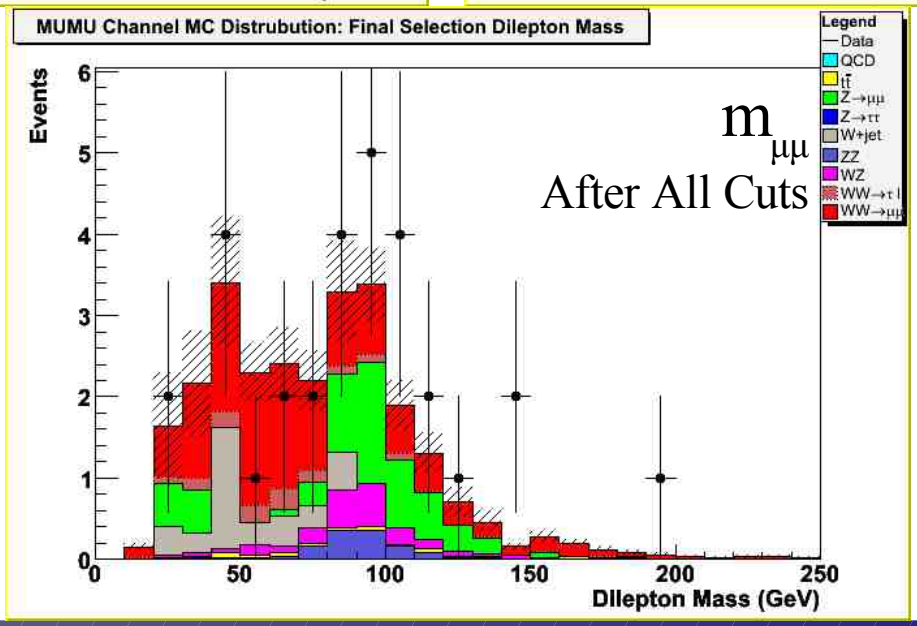
μμ Signal Selection

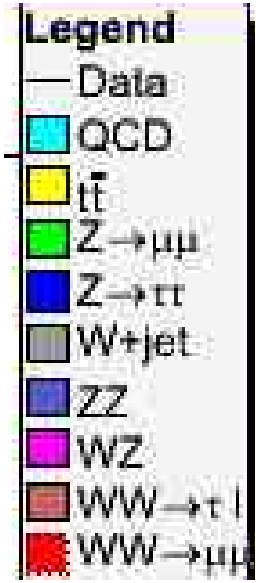
- Significance optimization led to this set of cuts:
  - Cut 1: MET > 30 GeV
  - Cut 2: Vector sum of MET, μ p_Ts < 19 GeV
  - Cut 3: $\Delta\varphi_{\mu\mu} < 2.4$ (plus acollinearity cut)
- Final selection cuts yield...
  - Errors reflect (stat + efficiency + charge mis-id) only!
  - Expected WW signal: 13.30 ± 0.39 events
  - Expected Σ backgrounds: 13.17 ± 1.57 events
  - Expected significance: 2.77 (including lumi uncertainty)
  - Expected total: 26.46 ± 1.63 events
  - Candidate events in data: 30 (observed significance 3.53)

μμ Signal Selection Plots









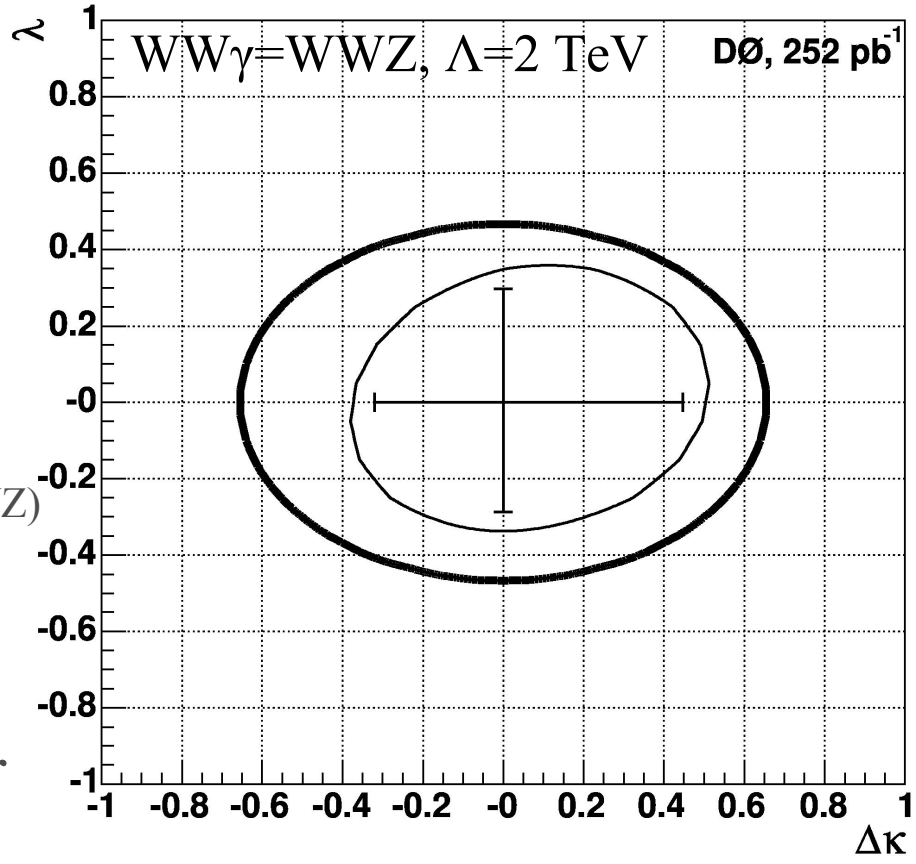
Cross Section Calculation

WORK IN PROGRESS!!!

- Individual channel cross section results:
  - ee: $\sigma_{WW} = 11.28 \pm 4.26$ (stat) ± 1.45 (syst) ± 0.69 (lumi) pb
  - eμ: $\sigma_{WW} = 7.61 \pm 1.83$ (stat) ± 0.52 (syst) ± 0.46 (lumi) pb
  - μμ: $\sigma_{WW} = 17.40 \pm 5.66$ (stat) ± 1.77 (syst) ± 1.06 (lumi) pb
    - Where "syst" includes uncertainty on the number of background events, the branching ratio, and A*ε
- Combined cross section measurement:
  - $\sigma_{WW} = 9.96 \pm 1.72$ (stat) ± 0.53 (syst) ± 0.61 (lumi) pb
    - Observed significance 6.75 (various systematics still under study...)
- Theoretical cross section (NNLO MCFM using CTEQ6M):
  - $\sigma_{WW} = 12.0 \pm 0.6$ (scale) ± 0.3 (PDF) pb

Anomalous Coupling Limits

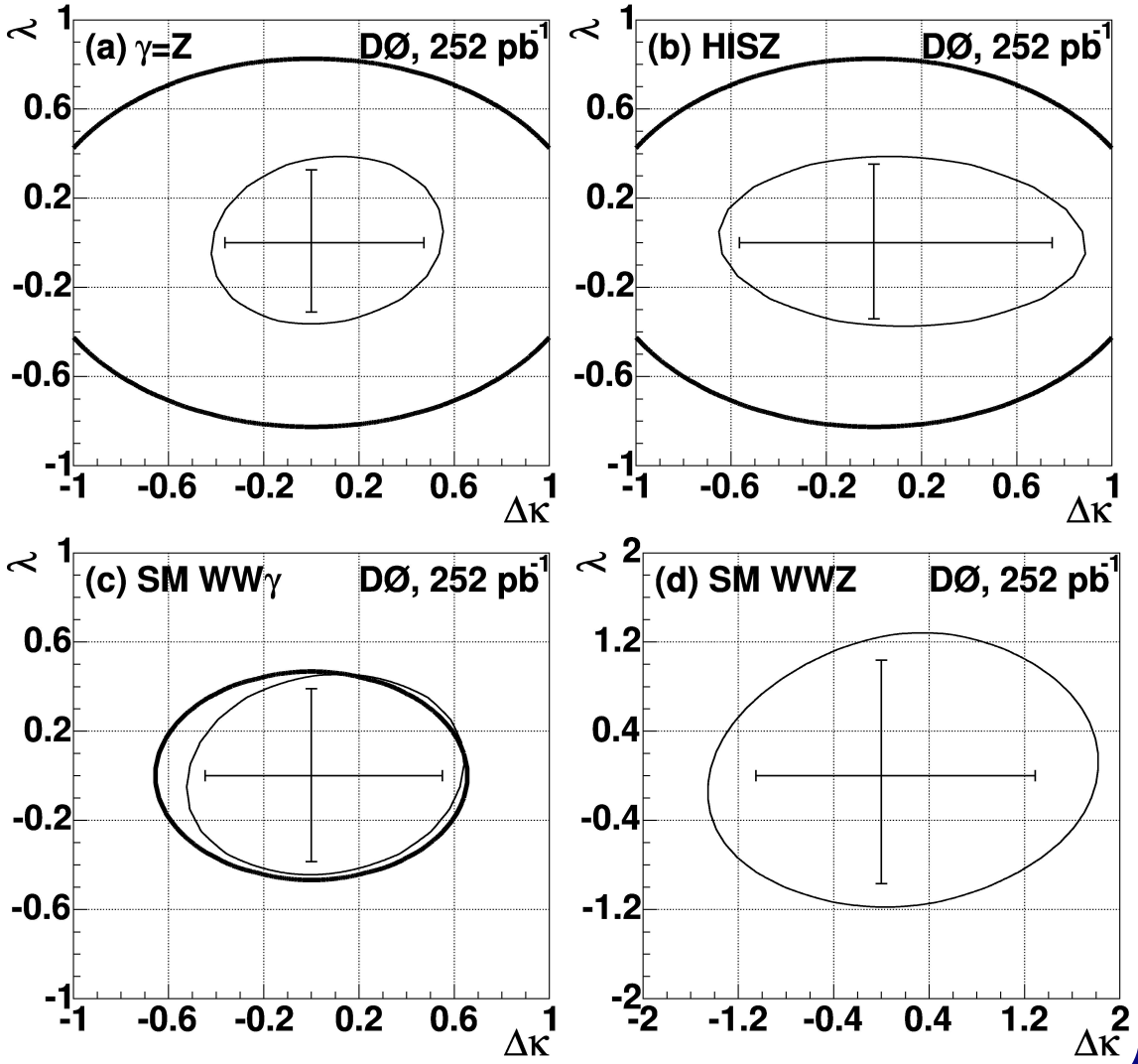
- Previous work extended a 252 pb^{-1} WW cross section study to produce AC limits
  - I was primary author of Phys. Rev. D74 057101
  - Limit set by comparing e/μ p_T distribution in data against grid of AC p_T distributions
  - Assumed various relationships between coupling parameters
    - $\Delta\kappa_\gamma=\Delta\kappa_Z$, $\lambda_\gamma=\lambda_Z$, $\Delta g_1^Z=0$ (WWγ=WWZ)
    - $SU(2)_L x U(1)_Y$ gauge symmetry enforced (HISZ)
    - SM WWγ or WWZ vertex, other vertex anomalous



Anomalous Coupling Limits

- 95% C.L. limits from 252 pb^{-1} AC study
  - Crosses are 1-D limits
  - Bold curve is unitarity limit

Coupling		95% C.L. Limits	Λ (TeV)
$WW\gamma = WWZ$	λ	$-0.31, 0.33$	1.5
	$\Delta\kappa$	$-0.36, 0.47$	
$WW\gamma = WWZ$	λ	$-0.29, 0.30$	2.0
	$\Delta\kappa$	$-0.32, 0.45$	
HISZ	λ	$-0.34, 0.35$	1.5
	$\Delta\kappa_\gamma$	$-0.57, 0.75$	
SM $WW\gamma$	λ_Z	$-0.39, 0.39$	2.0
	$\Delta\kappa_Z$	$-0.45, 0.55$	
SM WWZ	λ_γ	$-0.97, 1.04$	1.0
	$\Delta\kappa_\gamma$	$-1.05, 1.29$	



Anomalous Coupling Limits

- New AC limits will be set for the 1 fb^{-1} data sample
  - The 252 pb^{-1} cross section analysis was not optimized with AC study in mind
    - $\mu\mu$ channel selection included $20 < m_{\mu\mu} < 80$ GeV dilepton mass cut
    - Removed sensitivity to high p_T muon pairs for AC limit setting
  - New 1 fb^{-1} AC analysis will attempt to gain sensitivity beyond simple increase in luminosity
    - High p_T charged leptons were not explicitly removed during cross section analysis for any channel
    - Plan to use 2-D lead vs. trail charged lepton p_T distribution
      - ACs tend to make both higher simultaneously
- Also investigating combination of AC limits from WW, $W\gamma$ and WZ final states at DØ

$WW \rightarrow \ell^- \nu \ell^+ \bar{\nu}$ Cross Section and Triple Gauge Couplings

WORK IN PROGRESS!!!

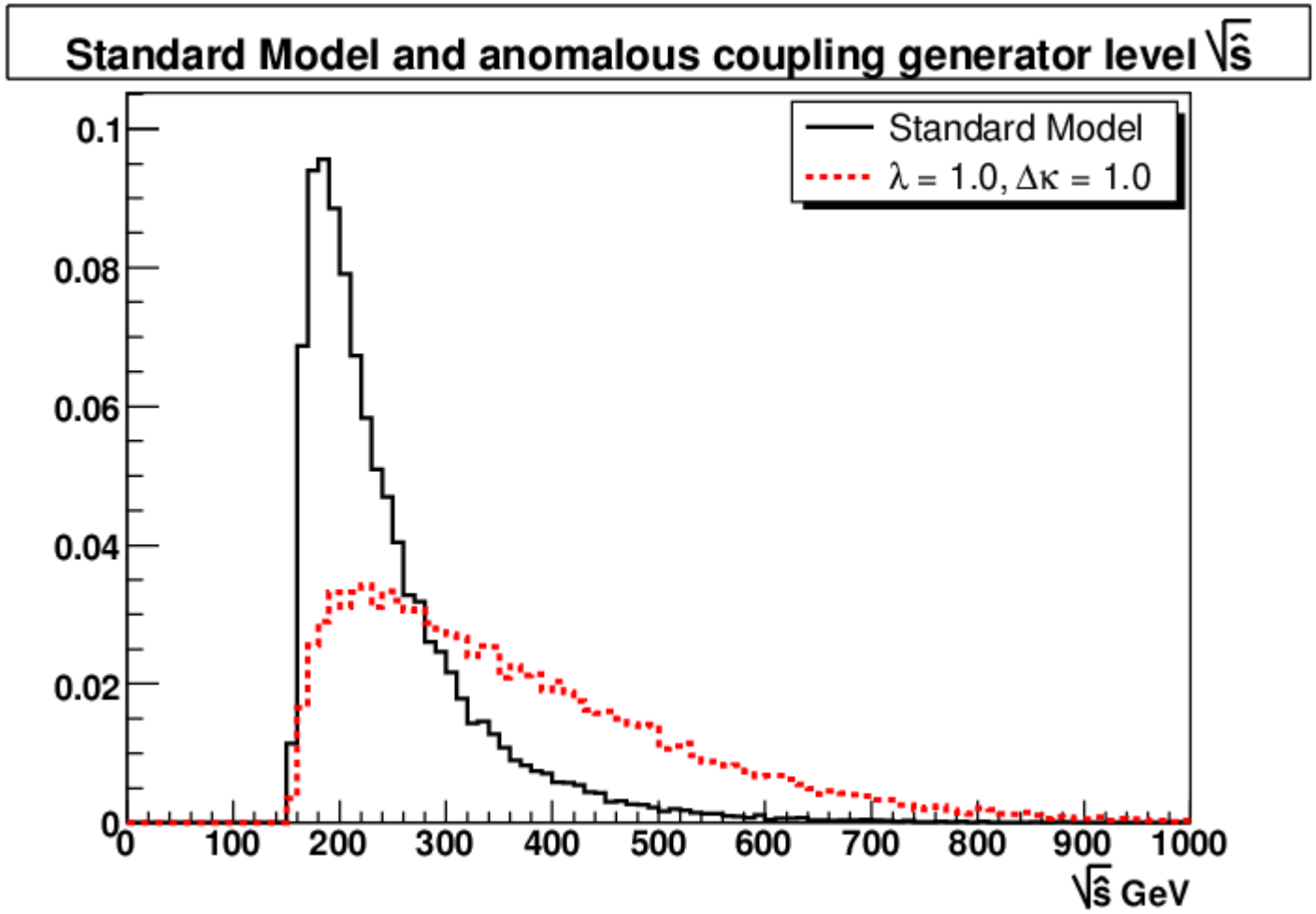
- Aiming for most accurate WW cross section measurement at a hadronic collider to date:
  - This: $9.96 \pm 1.72\,(\text{stat}) \pm 0.53\,(\text{syst}) \pm 0.61\,(\text{lumi})$ pb ($1\,\text{fb}^{-1}$)
  - DØ: $13.8^{+4.3}_{-3.8}(\text{stat})^{+1.2}_{-0.9}(\text{syst}) \pm 0.9\,(\text{lum})$ pb ($230\,\text{pb}^{-1}$)
    - Latest DØ published limit (PRL 94, 151801 (2005))
  - CDF: $13.6 \pm 2.3\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 1.2\,(\text{lum})$ pb ($825\,\text{pb}^{-1}$)
    - CDF Moriond 2006 result (FERMILAB-CONF-06-115-E)
- Seek to improve Tevatron limits on anomalous trilinear gauge couplings in $WW \rightarrow \ell\ell$ channel
  - Current focus of efforts!
  - Updating method to improve beyond simple lumi increase
  - Investigating combination of WW AC limits with WZ and $W\gamma$

Backup Slides

Michael Cooke

WW Center of Mass Energy

- Both curves are unit normalized (anomalous couplings increase the production cross section)



MC Cross Sections

Process	σ (pb)
WW (inclusive)	12.0
$Z/\gamma* \rightarrow \ell\ell$ ($15 < m_Z < 60$ GeV)	465.0
$Z/\gamma* \rightarrow \ell\ell$ ($60 < m_Z < 130$ GeV)	241.59
$Z/\gamma* \rightarrow \ell\ell$ ($130 < m_Z < 250$ GeV)	2.0
$t\bar{t}$	6.54
WZ (inclusive)	3.68
$W\gamma \rightarrow \ell\nu\gamma$ (ISR & Trilinear)	1.85
$W\gamma \rightarrow \ell\nu\gamma$ (FSR)	8.76
ZZ (inclusive)	1.42
$W \rightarrow \ell\nu$	2582.7

Charge Mis-ID Correction

- MC charge mis-ID rate does not match that in data
  - $Z \rightarrow \ell\ell$ and WW samples must be corrected for this
- $Z \rightarrow ee/\mu\mu$ MC events are compared to $Z \rightarrow ee/\mu\mu$ candidates in data, and charge mis-ID rate is measured
  - ee: MET < 20, $80 < m_{ee} < 100$ GeV, lead e in CC
  - $\mu\mu$: MET < 20, $70 < m_{\mu\mu} < 110$ GeV, $|(1/p_{T,lead}) / \sigma_{1/pT}| > 15$
  - If lead lepton's charge matches trail's, the trailing lepton's charge is considered misidentified

Lepton	Data CMID Rate (%)	MC CMID Rate (%)	MC Scaling Factor
CC Electrons	0.7807 ± 0.0625	0.1083 ± 0.0125	7.2081 ± 1.0104
EC Electrons	4.3778 ± 0.2211	1.8801 ± 0.0670	2.3285 ± 0.1439
Muons	0.1541 ± 0.0363	0.0404 ± 0.0044	3.8179 ± 0.9898
CC $e\mu$ Events	—	—	6.2752 ± 0.7389
EC $e\mu$ Events	—	—	2.3547 ± 0.1426

ee Channel Preselection

- Either electron fires a single EM trigger

Trigger Version	Single Electron Triggers Used
v8-v11	EM_HI EM_HI_SH EM_HI_2EM5_SH
v12	E1_SH30 E1_SHT20 E2_SHT20 E3_SHT20
v13	E1_SH30 E1_SHT22 E2_SHT22 E3_SHT22
v14	E1_SH35 E3_SH35 E1_SHT25 E3_SHT25 E1_T13SHT15 E1_T15SH20 E3_T13SHT15 E3_T15SH20

- $\Delta R(e_{Lead}, e_{Trail}) > 0.8$
- $\Delta Z_{Track}(e_{Lead}, e_{Trail}) < 2.0$ and $\Delta Z(pvtx, e_{Lead}) < 2.0$ cm
- $p_{T,Lead} > 25$, $p_{T,Trail} > 15$
- Opposite signed electrons
- At least one electron within CC

ee Channel Acceptance * Efficiency

Cut	Acceptance	Rel. Acc.
Electrons in CC or EC; at least one in CC	61.83±0.08%	—
Calorimeter ϕ module boundary cut	44.52±0.08%	72.0±0.2%
$\Delta R_{ee} > 0.8$	43.56±0.08%	97.9±0.3%
$p_{T,lead} > 15$ GeV, $p_{T,trail} > 15$ GeV	39.67±0.09%	91.1±0.3%
$p_{T,lead} > 20$ GeV, $p_{T,trail} > 15$ GeV	39.51±0.09%	90.7±0.3%
$p_{T,lead} > 25$ GeV, $p_{T,trail} > 15$ GeV	38.71±0.09%	88.9±0.3%
$p_{T,lead} > 25$ GeV, $p_{T,trail} > 20$ GeV	35.47±0.09%	81.4±0.3%
Cut, $p_{T,lead}/p_{T,trail}$ (GeV)	$A \times \varepsilon$	Rel. Eff.
e Preselection, 15/15	36.37±0.09%	91.7±0.3%
e Preselection, 20/15	36.23±0.09%	91.7±0.3%
e Preselection, 25/15	35.49±0.09%	91.7±0.3%
e Preselection, 25/20	32.55±0.09%	91.8±0.3%
Tight Likelihood, 15/15	18.13±0.10%	49.9±0.3%
Tight Likelihood, 20/15	18.07±0.10%	49.9±0.3%
Tight Likelihood, 25/15	17.75±0.10%	50.0±0.3%
Tight Likelihood, 25/20	16.57±0.10%	50.9±0.3%
Triggered Event, 15/15	17.87±0.10%	98.6±0.8%
Triggered Event, 20/15	17.86±0.10%	98.8±0.8%
Triggered Event, 25/15	17.69±0.10%	99.6±0.4%
Triggered Event, 25/20	16.53±0.10%	99.8±0.2%

ee Signal Selection

- Cut 1
  - MET > 30
- Cut 2
  - VSum < 20
- Cut 3
  - MET > 45 in $|M_Z - M_{ee}| < 7$
- Uncertainty indicates (stat + efficiency + charge mis-ID)

	Number of Events Remaining After:			
Sample	Preselection	Cut 1	Cut 2	Cut 3
$Z \to ee$	43250.6	94.36	8.09	1.95
$Z \to \tau\tau$	118.6	5.15	1.58	1.29
$t\bar{t}$	18.0	15.02	0.82	0.81
WZ	23.0	6.06	2.01	1.42
$W\gamma$	3.9	2.37	1.83	1.79
ZZ	4.5	2.64	1.87	1.44
W+jet	11.3	8.00	6.89	6.00
QCD	18.5	0.29	0.04	0.04
Sum Bkg.	43448.5 ±132.7	133.88 ±5.58	23.13 ±2.24	14.72 ±1.69
WW	28.2	18.51	15.23	14.47
Significance	0.14	1.499	2.46	2.68
Sum All	40613.5 ±132.8	152.39 ±5.62	38.36 ±2.32	29.20 ±1.78
Data	41253	176	36	29

eμ Channel Acceptance * Efficiency

Cut	Acceptance	Rel. Acc.
Electron in CC or EC; muon satisfies $\lvert\eta_{D,muon}\rvert < 2.0$	70.7±0.1%	—
Calorimeter ϕ module boundary cut for electron	61.1±0.1%	86.4±0.2%
$\Delta R_{e\mu} > 0.5$	60.5±0.1%	99.0±0.3%
$p_{T,e} > 15$ GeV, $p_{T,\mu} > 15$ GeV	55.2±0.1%	91.2±0.3%
$p_{T,e} > 20$ GeV, $p_{T,\mu} > 15$ GeV	52.0±0.1%	85.9±0.3%
$p_{T,e} > 25$ GeV, $p_{T,\mu} > 15$ GeV	47.6±0.1%	78.6±0.3%
$p_{T,e} > 25$ GeV, $p_{T,\mu} > 20$ GeV	45.6±0.1%	75.3±0.3%
$p_{T,lead} > 15$ GeV, $p_{T,trail} > 15$ GeV	55.2±0.1%	91.2±0.3%
$p_{T,lead} > 20$ GeV, $p_{T,trail} > 15$ GeV	55.0±0.1%	90.8±0.3%
$p_{T,lead} > 25$ GeV, $p_{T,trail} > 15$ GeV	53.8±0.1%	88.9±0.3%
$p_{T,lead} > 25$ GeV, $p_{T,trail} > 20$ GeV	49.3±0.2%	81.4±0.3%
Cut (p_T conditions (GeV))	$A \times \varepsilon$	Rel. Eff.
Final efficiency ($p_{T,e}$ >15, $p_{T,\mu}$ >15)	22.8±0.2%	41.3±0.4%
Final efficiency ($p_{T,e}$ >20, $p_{T,\mu}$ >15)	22.8±0.2%	43.8±0.4%
Final efficiency ($p_{T,e}$ >25, $p_{T,\mu}$ >15)	22.0±0.2%	46.2±0.4%
Final efficiency ($p_{T,e}$ >25, $p_{T,\mu}$ >20)	21.1±0.2%	46.2±0.4%
Final efficiency ($p_{T,lead}$ >15, $p_{T,trail}$ >15)	22.8±0.2%	41.3±0.4%
Final efficiency ($p_{T,lead}$ >20, $p_{T,trail}$ >15)	22.8±0.2%	41.5±0.4%
Final efficiency ($p_{T,lead}$ >25, $p_{T,trail}$ >15)	22.6±0.2%	42.1±0.4%
Final efficiency ($p_{T,lead}$ >25, $p_{T,trail}$ >20)	21.7±0.2%	44.1±0.4%

eμ Signal Selection

- Cut 1
  - MET > 20
- Cut 2
  - VSum < 19
- Cut 3
  - MET > 40 if $\Delta\varphi_{e\mu} > 2.8$
- Uncertainty indicates (stat + efficiency + charge mis-ID)

	Number of Events Remaining After:			
Sample	Preselection	Cut 1	Cut 2	Cut 3
$Z \to \tau\tau$	256.28	43.06	28.32	3.62
Z+jet	59.27	23.48	4.39	1.51
$t\bar{t}$	35.11	32.65	3.26	2.92
WZ	4.28	3.54	1.46	1.25
$W\gamma$	4.71	3.90	3.22	2.82
ZZ	0.67	0.30	0.10	0.08
W+jet	12.83	10.04	8.59	7.43
QCD	9.50	3.00	0.70	0.22
Sum Bkg.	382.65 ±12.31	119.98 ± 4.72	50.05 ± 2.49	19.18 ± 1.76
WW	62.00	50.83	43.03	39.00
Significance	2.94	3.89	4.46	5.11
Sum All	444.65 ±12.36	170.81 ± 4.81	93.08 ± 2.61	58.18 ± 1.91
Data	462	164	92	48

μμ Channel Acceptance * Efficiency

Cut	Acceptance	Rel. Acc.
Muons satisfy $\lvert\eta_{D,muon}\rvert < 2.0$	$73.59 \pm 0.04\%$	—
$\Delta R_{\mu\mu} > 0.5$	$72.96 \pm 0.04\%$	$99.14 \pm 0.08\%$
$p_{T,lead} > 15$ GeV, $p_{T,trail} > 15$ GeV	$64.2 \pm 0.2\%$	$88.0 \pm 0.3\%$
$p_{T,lead} > 20$ GeV, $p_{T,trail} > 15$ GeV	$63.9 \pm 0.2\%$	$87.6 \pm 0.3\%$
$p_{T,lead} > 25$ GeV, $p_{T,trail} > 15$ GeV	$62.5 \pm 0.3\%$	$85.7 \pm 0.4\%$
$p_{T,lead} > 25$ GeV, $p_{T,trail} > 20$ GeV	$56.6 \pm 0.4\%$	$77.5 \pm 0.5\%$
Cut, $p_{T,lead}/p_{T,trail}$ (GeV)	$A \times \varepsilon$	Rel. Eff.
Medium Muon ID, 15/15	$32.0 \pm 0.1\%$	$49.8366 \pm 0.2\%$
Medium Muon ID, 20/15	$31.9 \pm 0.1\%$	$49.8664 \pm 0.3\%$
Medium Muon ID, 25/15	$31.2 \pm 0.1\%$	$49.9652 \pm 0.3\%$
Medium Muon ID, 25/20	$28.8 \pm 0.2\%$	$50.9808 \pm 0.4\%$
Loose Muon Track Match, 15/15	$27.4 \pm 0.4\%$	$85.6857 \pm 1.1\%$
Loose Muon Track Match, 20/15	$27.3 \pm 0.4\%$	$85.6806 \pm 1.2\%$
Loose Muon Track Match, 25/15	$26.8 \pm 0.4\%$	$85.6653 \pm 1.2\%$
Loose Muon Track Match, 25/20	$24.7 \pm 0.3\%$	$85.7522 \pm 1.3\%$
Tight Muon Isolation, 15/15	$24.6 \pm 0.3\%$	$89.784 \pm 1.6\%$
Tight Muon Isolation, 20/15	$24.5 \pm 0.3\%$	$89.7874 \pm 1.7\%$
Tight Muon Isolation, 25/15	$24.0 \pm 0.3\%$	$89.7848 \pm 1.7\%$
Tight Muon Isolation, 25/20	$22.2 \pm 0.3\%$	$89.7868 \pm 1.8\%$
Triggered Event, 20/15	$21.4 \pm 0.3\%$	$87.3754 \pm 1.3\%$
Triggered Event, 25/15	$21.0 \pm 0.3\%$	$87.3679 \pm 1.5\%$

μμ Signal Selection

- Cut 1
  - MET > 30
- Cut 2
  - VSum < 19
- Cut 3
  - $\Delta\varphi_{\mu\mu} < 2.45$
  - $\cos(\Delta\varphi_{MET,\mu}) < 0.98$
- Uncertainty indicates:
  - (stat + efficiency + charge mis-ID)

	Number of Events Remaining After:			
Sample	Preselection	Cut 1	Cut 2	Cut 3
$Z \to \mu\mu$	54154.0	1276.06	662.84	5.87
$Z \to \tau\tau$	158.1	11.82	3.94	0.00
$t\bar{t}$	20.1	17.01	0.80	0.44
WZ	29.5	9.77	3.71	2.05
ZZ	5.2	3.31	2.37	1.32
W+jet	5.2	4.70	4.25	3.49
QCD	0.0 (± 2.9)	0.0 (± 0.99)	0.0 (± 0.21)	0.0 (± 0.02)
Sum Bkg.	54372.2 ± 77.0	1322.67 ± 10.11	677.915 ± 6.91	13.17 ± 1.57
WW	39.6	27.85	21.09	13.30
Significance	0.16	0.76	0.80	2.58
Sum All	54411.7 ± 77.0	1350.52 ± 10.15	699.01 ± 6.94	26.46 ± 1.63
Data	49073	1525	794	30

Highest Dilepton Mass Event

- After final selection cuts, the highest dilepton mass event was found in the μμ channel
  - Run/Event: 209062 / 90876535
  - Inv Mass: 194.651
  - Lead pT: 49.6535
  - Lead phi: 6.07822
  - Lead eta: -1.3959
  - Trail pT: 43.2248
  - Trail phi: 2.11064
  - Trail eta: 1.39134
  - MET: 40.7698
  - MET phi: 3.76489