

Search for $H \rightarrow WW$ and measurement of the WW cross section



THE UNIVERSITY
of
WISCONSIN
MADISON



Will Parker

University of Wisconsin – Madison

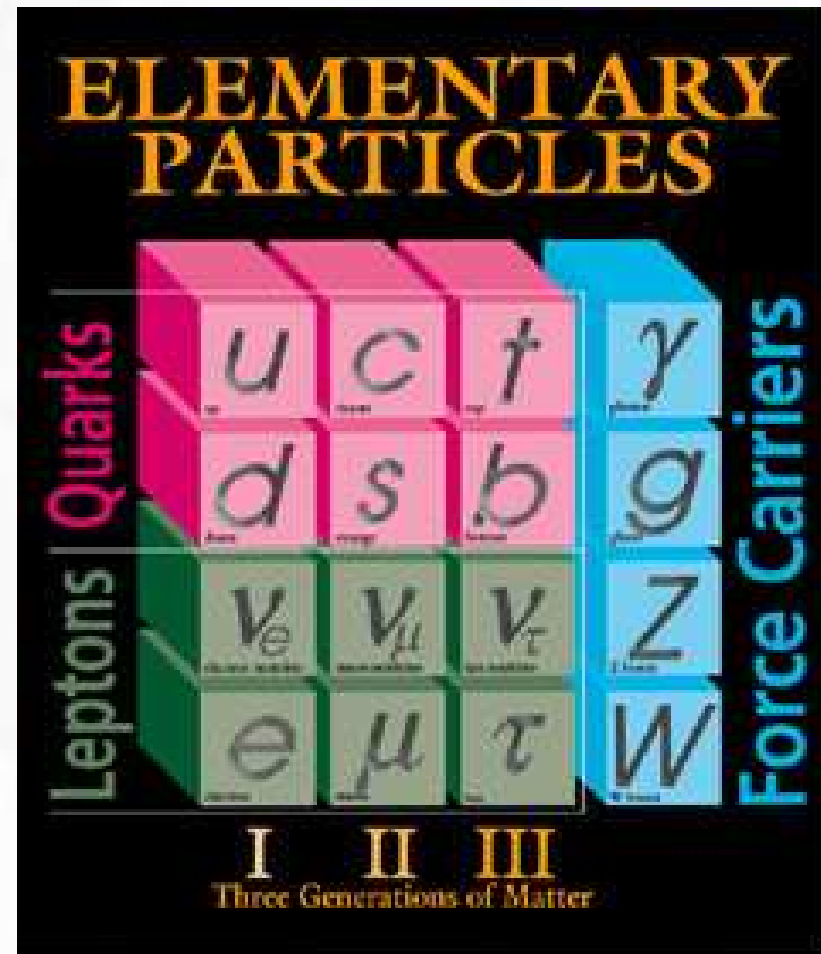
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Outline

- Introduction
- Experiment
- Simulation
- Analysis
- Results
- Conclusion

The Standard Model

- Twelve fermions (plus corresponding antiparticles) that make up matter
- Three fundamental forces carried by four vector bosons
- Mass asymmetry between W/Z and photon
- One scalar boson: Higgs Boson, predicted but not yet observed



EW Symmetry Breaking and the Higgs

- A Higgs or Higgs-like mechanism is needed
- Gives mass to the W and Z bosons through spontaneous symmetry breaking
- Predicts the existence of Higgs Boson, which couples to particle mass

$$\mathcal{L}_{W,H} = -\frac{1}{2}W_{\mu\nu}^+W^{-\mu\nu} + \frac{1}{4}g^2v^2W_\mu^+W_\mu^- + \frac{1}{2}(\partial_\nu H)(\partial^\nu H)$$

$$-v^2\lambda H^2 + \frac{1}{2}g^2vHW_\mu^+W_\mu^- + \frac{g^2}{4}H^2W_\mu^+W_\mu^-$$

W Mass (points to $\frac{1}{4}g^2v^2W_\mu^+W_\mu^-$)
H Mass (points to $-v^2\lambda H^2$)
HWW Interaction (points to $\frac{1}{2}g^2vHW_\mu^+W_\mu^-$)

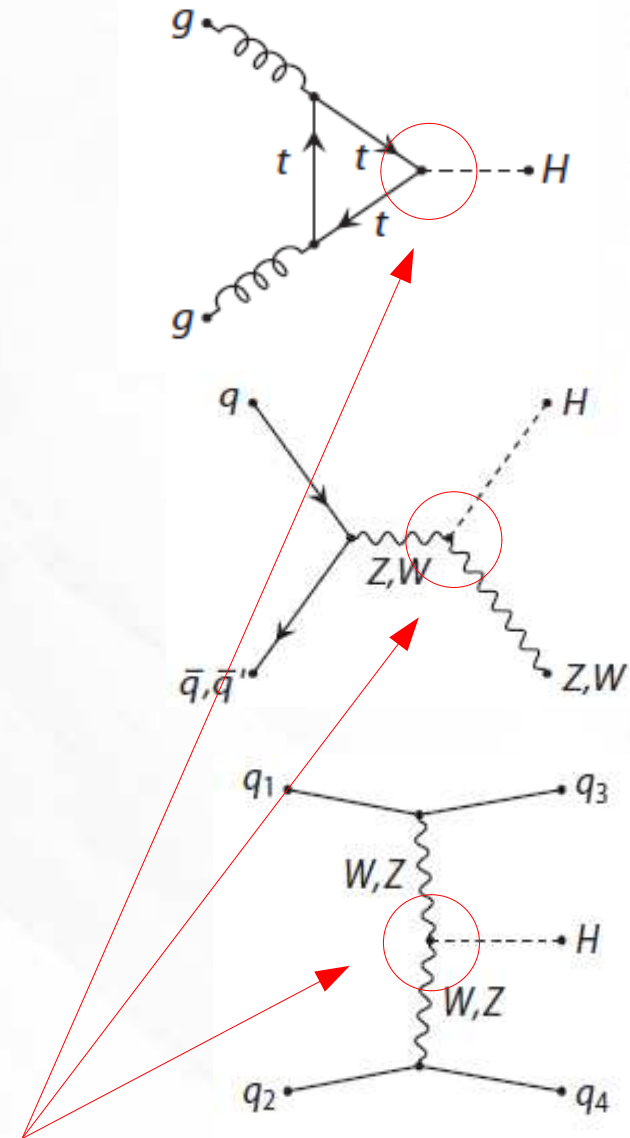
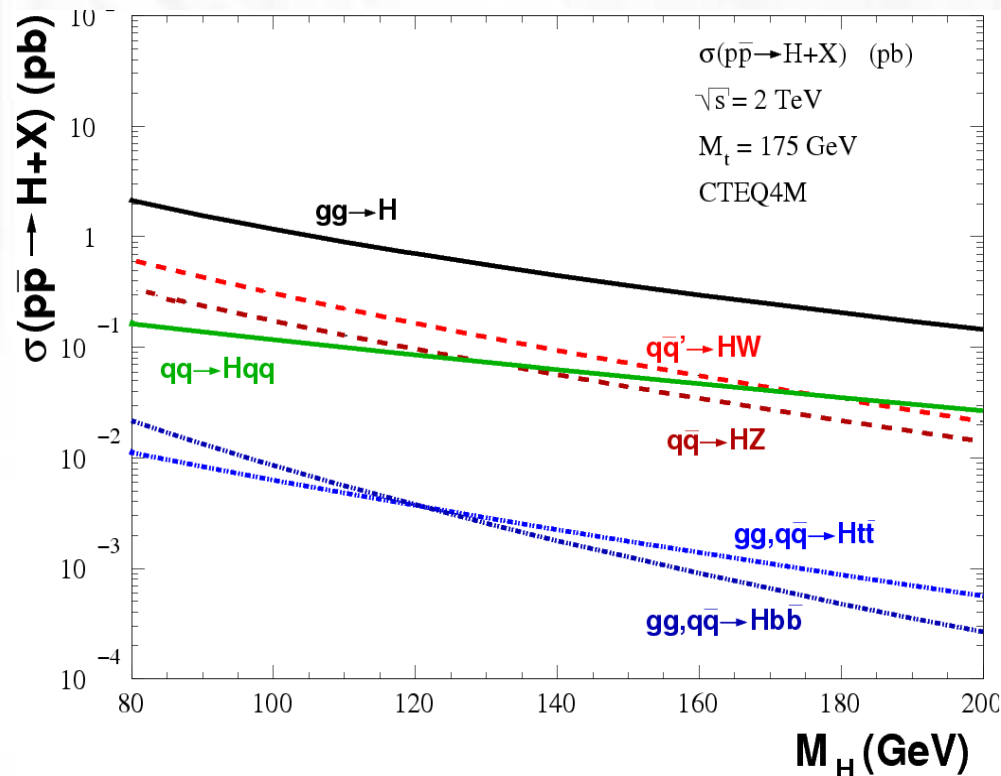
- Fermions could gain mass by the same method

$$\text{Mass: } \frac{g_f v}{\sqrt{2}} \quad \text{Coupling: } \frac{g_f}{\sqrt{2}}$$

- All particles couple to Higgs proportional to their mass

Higgs Production at CDF

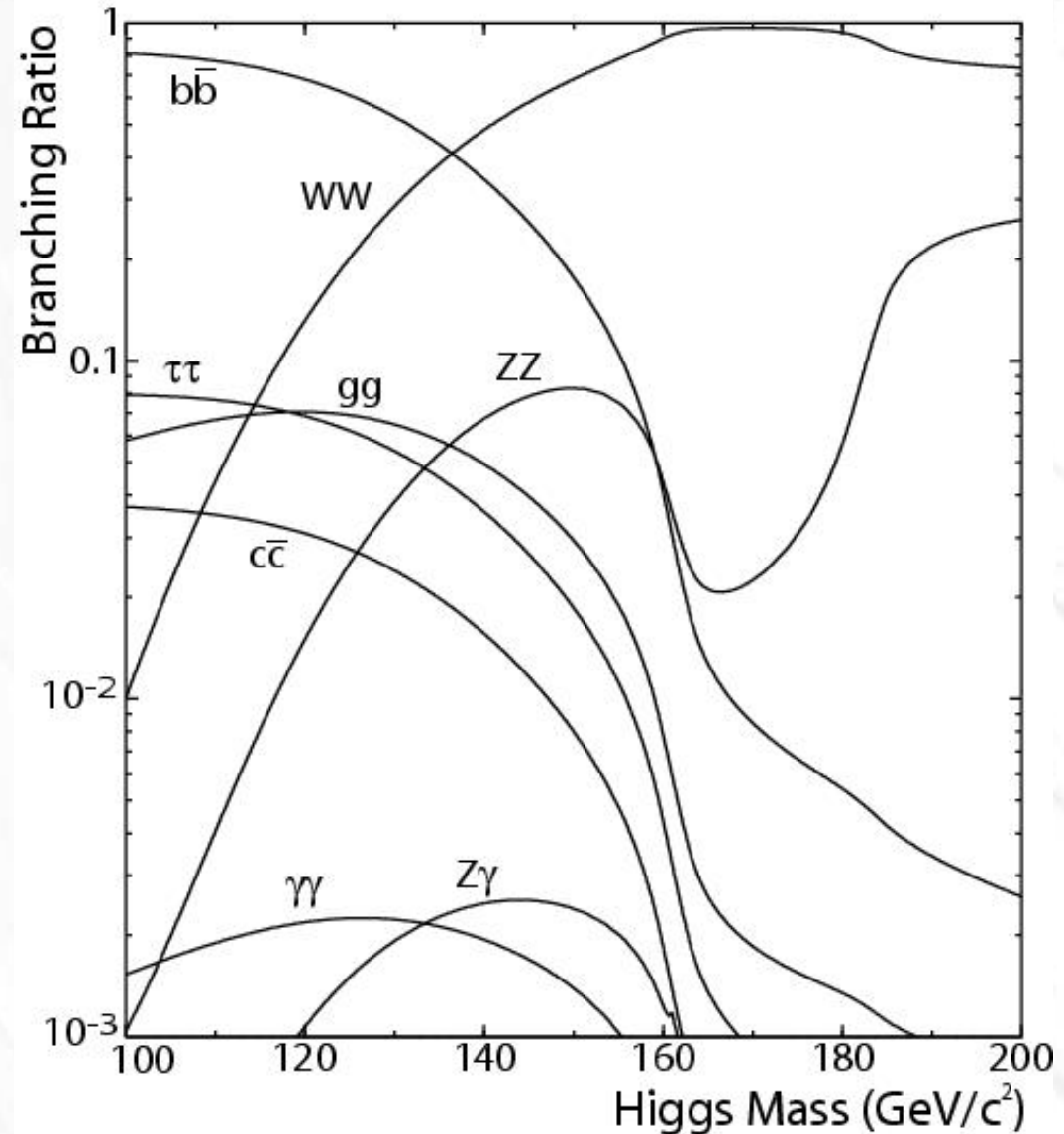
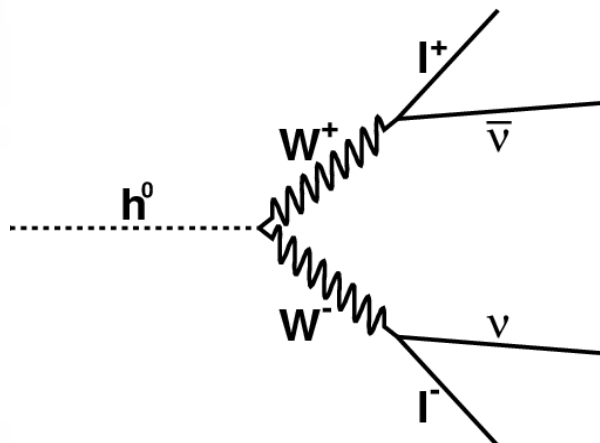
- gg fusion is dominant overall
- Here we study $H \rightarrow WW + 2 \text{ jets}$
- Associative production and vector boson fusion become comparable and distinctive due to extra gauge boson or forward jets



Coupling proportional to mass

Higgs Decay

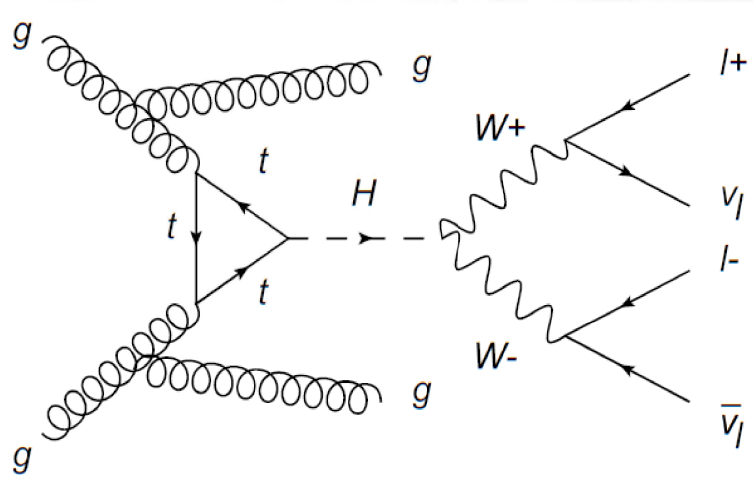
- $H \rightarrow WW$ is dominant above 123 GeV
- Leptonic W decay (33% BR) is easier to study
- Require $W \rightarrow e, \mu$ or $W \rightarrow \tau \rightarrow e, \mu$
- Leptons can come from $H \rightarrow WW$ or associated gauge boson



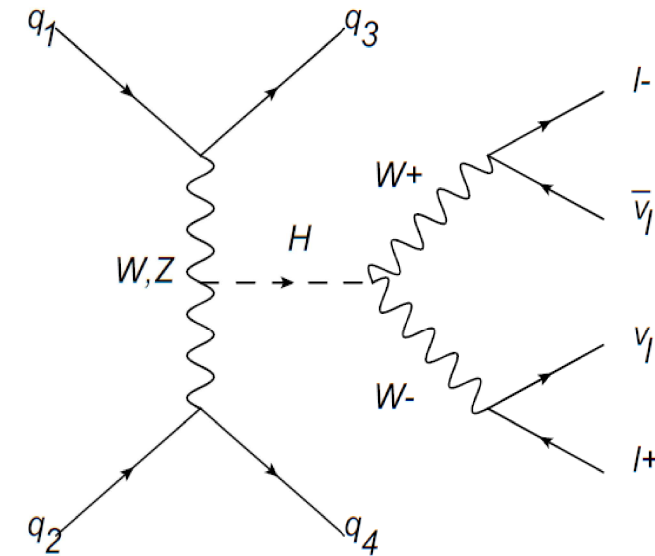
Final State

Require exactly two leptons, Met, and 2 or more jets

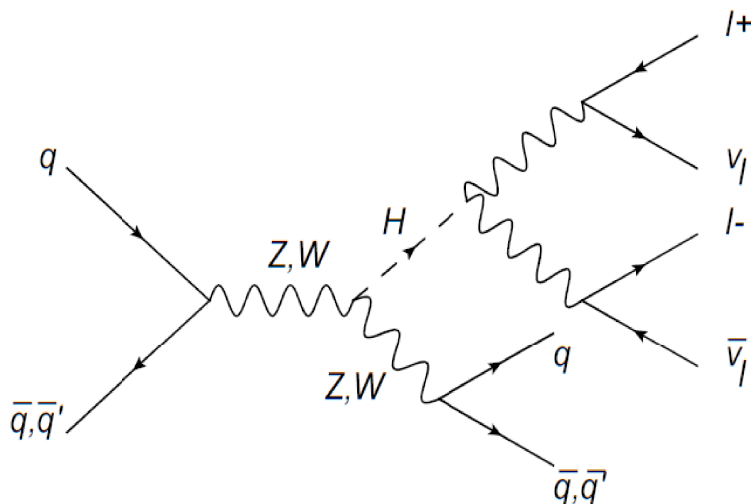
- Gluon fusion with ISR



- Vector boson fusion

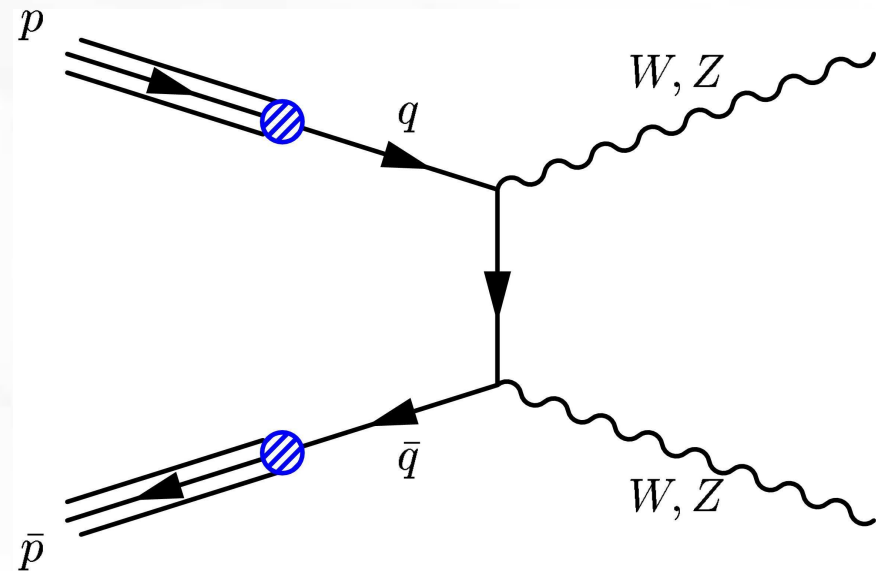
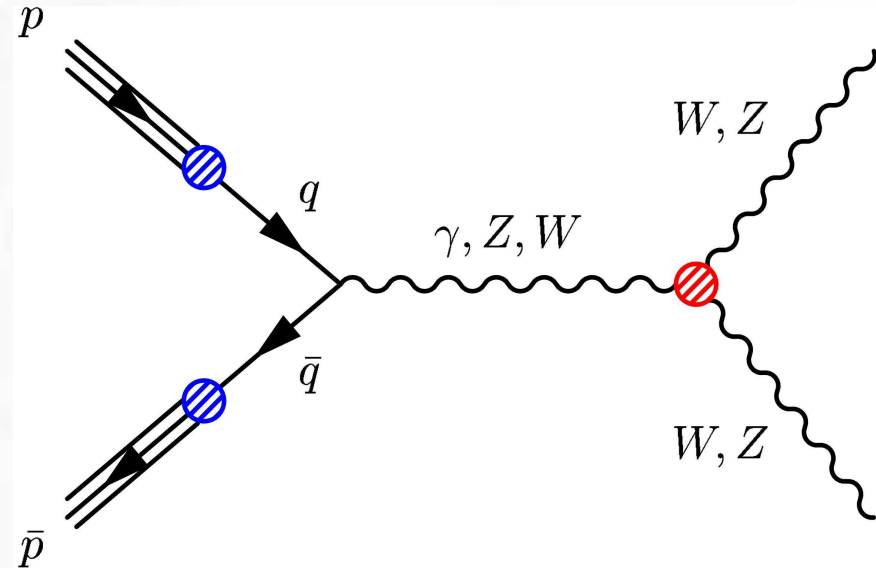


- Associative production with hadronic decay



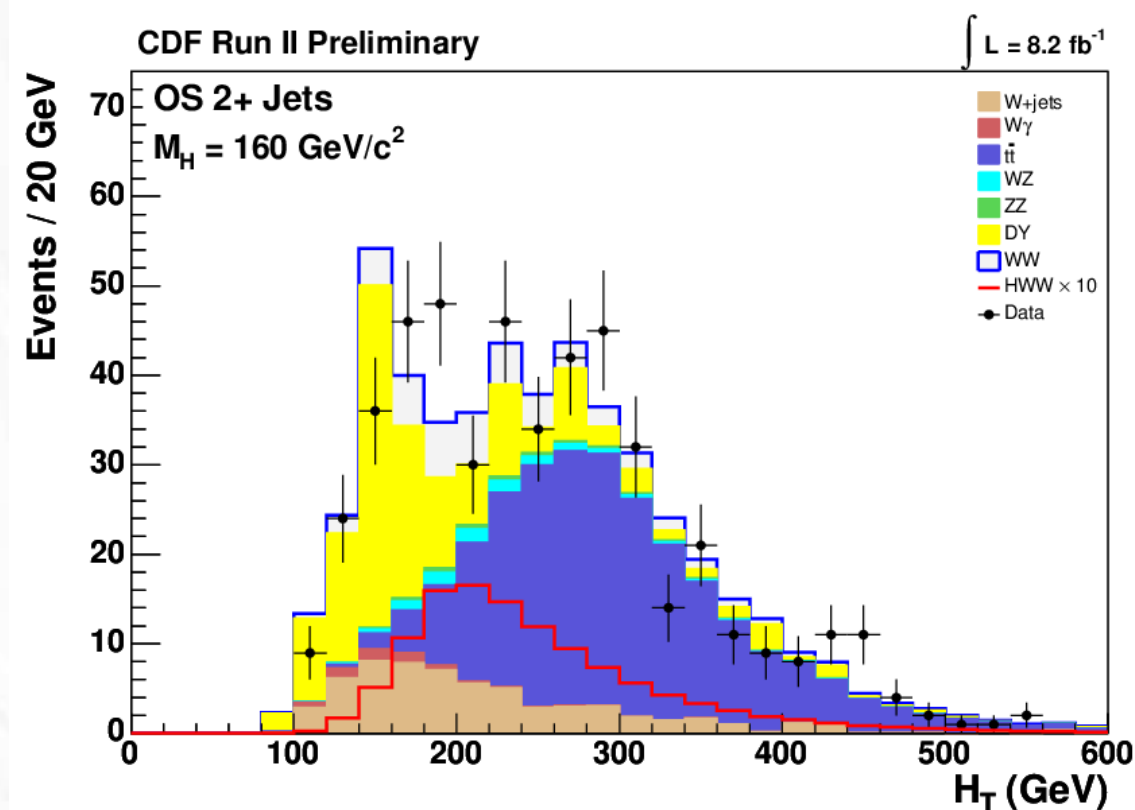
WW Production

- Significant background for Higgs search
- $pp \rightarrow WW + 2\text{jets}$ is a NNLO process
- Tests NNLO MC that is needed for Higgs search
- Triple gauge coupling
- Sensitive to new physics



Dominant Backgrounds

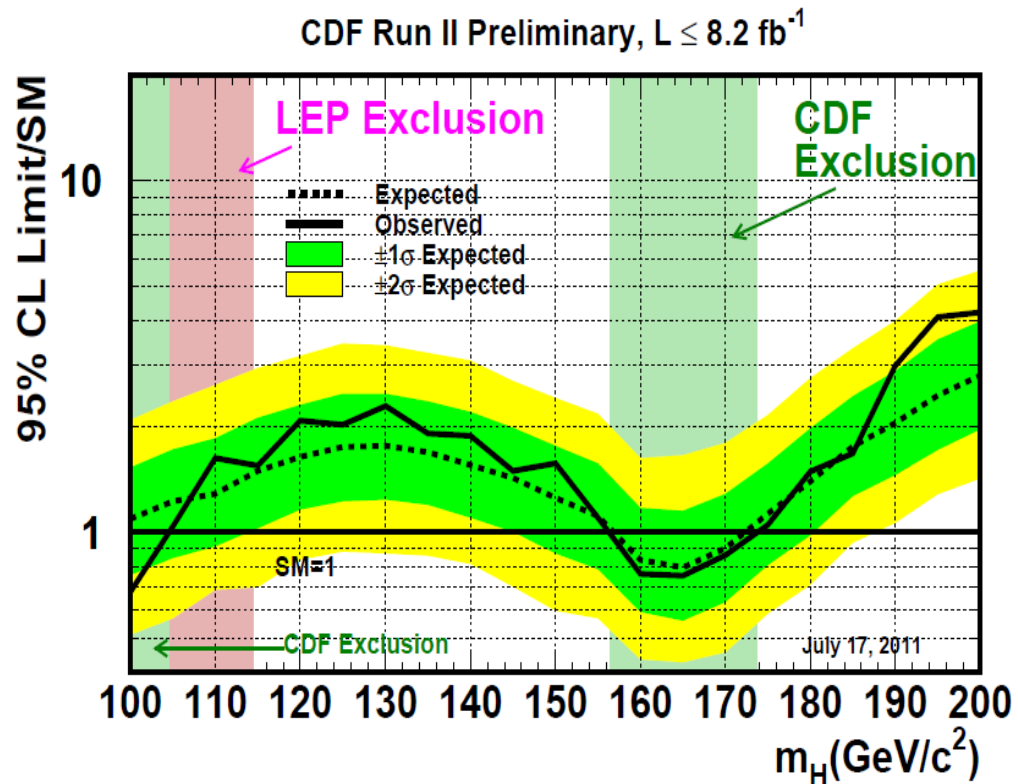
- $t\bar{t}$ ($t \rightarrow Wb$)
- Drell-Yan (Jet mismeasurement resulting in missing E_T)
- WW
- W +jets
- W +gamma
- WZ
- ZZ



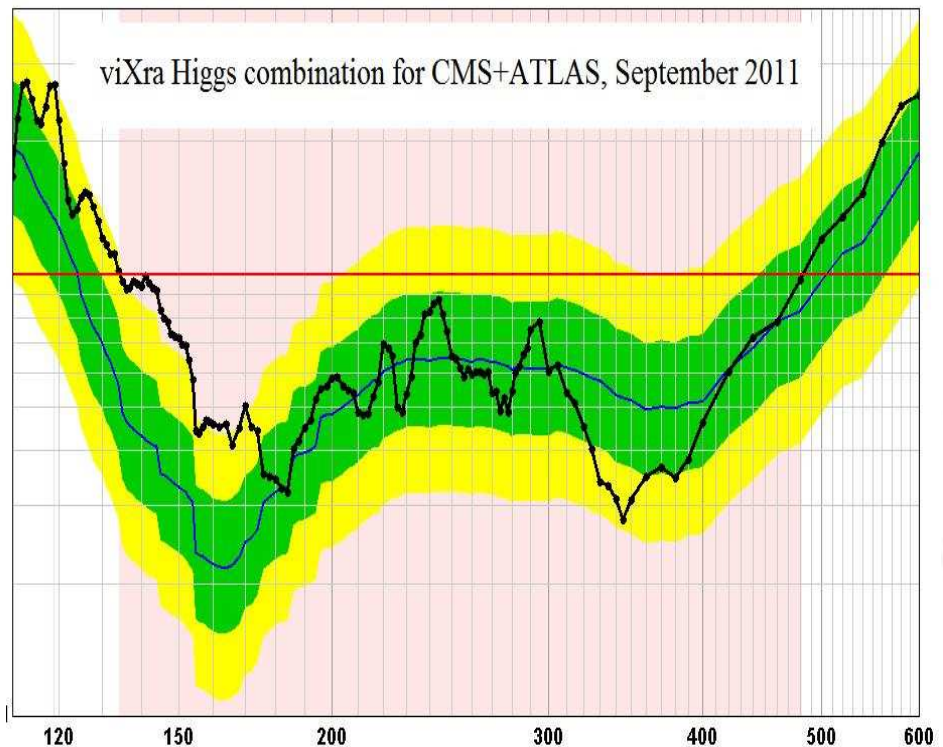
Scalar sum of transverse energy of
leptons, met, and jets

Current State of Higgs Exclusion

Limit set by Tevatron



Limit set by LHC



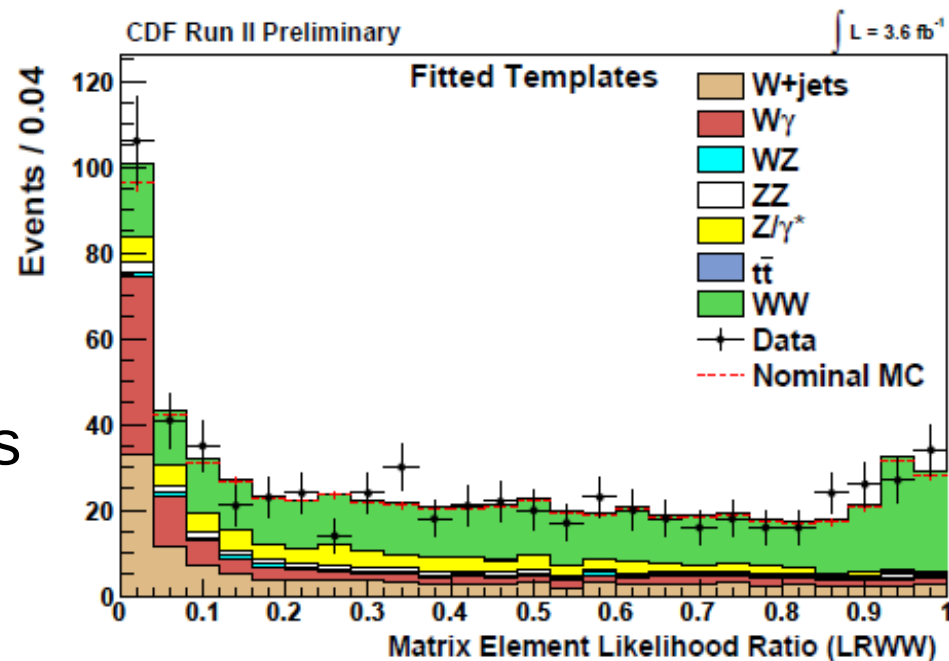
LHC observes an excess around 130 GeV, where $H \rightarrow WW$ is still the most powerful contributor to the CDF analysis

Limitations of Previous Analysis

- Used Pythia to generate $H \rightarrow WW$ signal and most backgrounds
- Used NLO MC to generate WW backgrounds
- MC is tuned to properly model the reconstructed momentum of the mother particles
- Does not reproduce the kinematics of the individual jets
- Dijet masses can be used to detect W or Z bosons, or the signature forward jets of VBF
- We update the background MC to NNLO where appropriate
- No measurements of massive diboson production with 2 jets have been performed before. This work will perform the first measurement as a necessary validation of the MCs predictions.

Current WW Cross Section Measurement

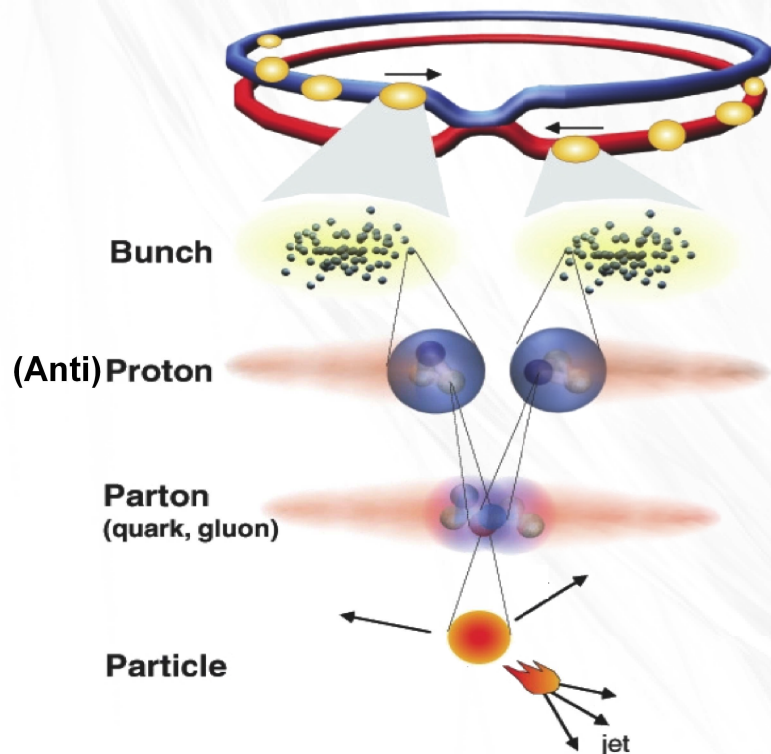
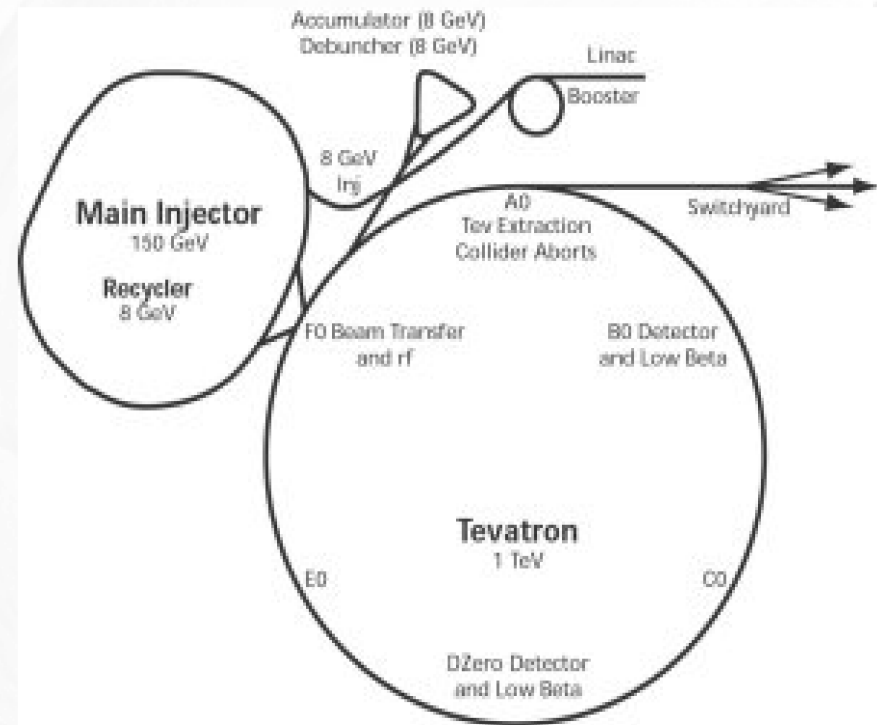
- CDF
- Uses 3.6 fb^{-1}
- Used matrix element based likelihood ratios
- Only events with no reconstructed jets
- $12.1 \pm 0.9 \text{ (stat)} + 1.6 \text{ (syst)}$
- D0
- Uses $224\text{--}252 \text{ pb}^{-1}$
- Cut based analysis
- Uses Pythia to model WW
- $13.8 \pm 4.3 \text{ (stat)} + 1.2 \text{ (syst)}$
- Our measurement
- Uses full dataset
- Uses NNLO MC
- Measures differential cross section as a function of jet energy and multiplicity



CDF data and templates

The Tevatron

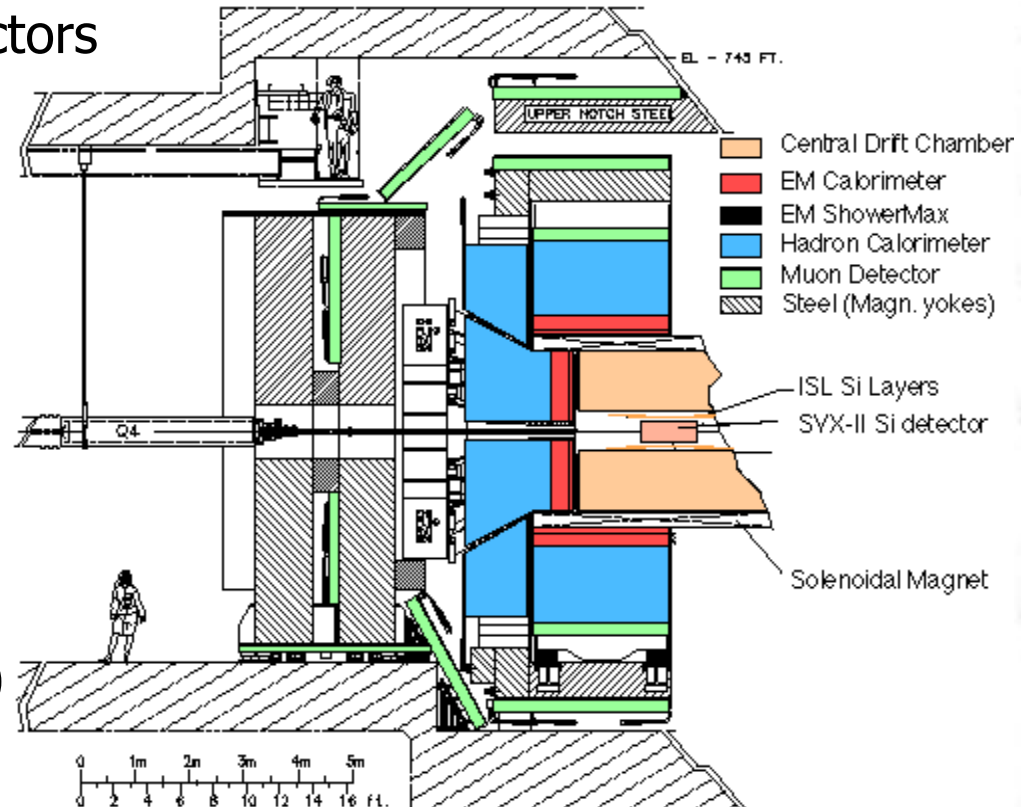
- Proton-antiproton collider
- 1km radius $\rightarrow$ 21 μ s revolution time
- $\sqrt{s} = 1.96$ TeV



- 36 bunches per beam
- 3×10^{11} protons and 0.8×10^{11} pbars per bunch
- Luminosity: $3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- 9.97 fb^{-1} of data collected
- This analysis uses 8.2 fb^{-1}

The CDF Detector

- Silicon Detector
 - Silicon microstrip detectors
 - $|\eta| < 2.0$
- Central Outer Tracker
 - Drift chamber
 - $|\eta| < 1.0$
- EM(H) Calorimeters
 - Pb(Fe)/scintillator
 - $|\eta| < 3.6$ (central+plug)
- Muon detectors
 - Wire chambers in proportional mode
 - Combined coverage out to $|\eta| < 1.5$
 - Scintillator tiles provide triggering and timing information



Electron Detection and Identification

- Two Categories

	TCE
Region	central
Fiducial	track fiducial to CES
Track p_T	≥ 10 (5 if $E_T < 20$)
Track $ z_0 $	≤ 60 cm
# Ax SL (5hits)	≥ 3
# St SL (5hits)	≥ 2
Conversion	$\neq 1$
E_{HAD}/E_{EM}	$\leq 0.055 + 0.00045 * E$
Iso/E_T	≤ 0.1
Lshr	≤ 0.2
E/P	$< 2.5 + 0.015 * E_T$
signed CES ΔX	$-3 \leq q * \Delta X \leq 1.5$ cm
CES $ \Delta Z $	< 3 cm
Track	Beam constrained

	PHX/PEM
Region	Plug
Pes2DEta	$1.2 < \eta < 2$ (2.8 PEM)
Had/Em	≤ 0.05
PEM3x3FitTower	true
$PEM3x3\chi^2$	≤ 10
Pes5x9U	≥ 0.65
Pes5x9V	≥ 0.65
Iso/Et	≤ 0.1
$\Delta R(\text{Pes}, \text{PEM})$	≤ 3.0
PHX only	
Track Match	True
NSiHits	≥ 3
Track $ Z_0 $	≤ 60 cm
PEM	Not above PHX track requirements

Or a likelihood discriminant
using many of the same
variables

Only use PHX

Stubbed Muons

Four categories of stubbed muons: CMUP, CMU, CMP, CMX

	CMUP/CMX
CMU Fid	$x\text{-fid} < 0 \text{ cm } z\text{-fid} < 0 \text{ cm}$
CMP Fid	$x\text{-fid} < 0 \text{ cm } z\text{-fid} < -3 \text{ cm}$
CMX Fid	$x\text{-fid} < 0 \text{ cm } z\text{-fid} < -3 \text{ cm}$
E_{em}	$\leq 2 + \max(0, (p - 100) * 0.0115)$
E_{had}	$\leq 6 + \max(0, (p - 100) * 0.028)$
Iso/Pt	≤ 0.1
NAxL(5 hits)	≥ 3
NStL(5 hits)	≥ 2
Track $ Z_0 $	$\leq 60 \text{ cm}$
Track $ D_0 $	$\leq 0.2 \text{ cm}$ (0.02cm if NSiHit > 0)
χ^2/dof	≤ 4 (3 if run ≤ 186598)
$ \Delta X_{CMU} $	$\leq 7 \text{ cm}$
$ \Delta X_{CMP} $	$\leq 5 \text{ cm}$
$ \Delta X_{CMX} $	$\leq 6 \text{ cm}$
ρ_{exit}	$> 140 \text{ cm}$ if CMX
CMP veto	No Bluebeam in CMP for run < 154449
CMX veto	No CMX for run < 150144 , No Miniskirt, No Keystone
Arches	Arches only for all run range
	Arches removing wedge 14 on West Side for run > 190697
Tracks	BcTrk (Larry's Correction if Data)

A CMP(CMU) muon should not be fiducial to the
CMU(CMP or CMX)

Stubbleless Muons

Minimum ionizing track pointing to CES/PES

	CMIOCES/CMIOPEs
E_{em}	$\leq 2 + \max(0, (p - 100) * 0.0115)$
E_{had}	$\leq 6 + \max(0, (p - 100) * 0.028)$
Iso/Pt	≤ 0.1
Uniqueness	Not a CMUP or CMX muon
Track $ Z_0 $	$\leq 60cm$
Track $ D_0 $	$\leq 0.2cm$ (0.02cm if NSiHit > 0)
$E_{em} + E_{had}$	$> 0.1GeV$
Central	Track CES Fiducial
NAL(5 hits)	≥ 3
NStL(5 hits)	≥ 3
χ^2/dof	≤ 3
	BcTrk (Larry Correction if Data)
Forward	Track PES Fiducial
Cot Hit Fraction	> 0.6
	No beam constraint on IO tracks

Other Leptons

- CMXMsKs: Same as CMX muon, but in the Miniskirt or Keystone detectors
 - $75^\circ < \Phi < 105^\circ$ (for $|\eta| < ?$ (Note says 0)), $225^\circ < \Phi < 315^\circ$
- BMU: Same as CMIOPEs muon, but with a stub in one of the IMU detectors
- CrkTrk: Similar to CMIOCES, but no minimum ionizing calorimeter or CES fiduciality requirements

	CrkTrk
Iso/Pt	≤ 0.1 using CDF Muon <i>or</i> ≤ 0.1 using nearest CDF EMObj with $\Delta R < 0.05$
Track $ Z_0 $	$\leq 60cm$
Track $ D_0 $	$\leq 0.2cm$ (0.02cm if NSiHit > 0)
χ^2/dof	≤ 3
NAL(5 hits)	≥ 3
NStL(5 hits)	≥ 3
Uniqueness	Not a CMUP or CMX muon
Is in Crack	Not Track CES or PES Fiducial
Conversion	$\neq 1$
	BcTrk (Larry Correction if Data)

Muon Coverage

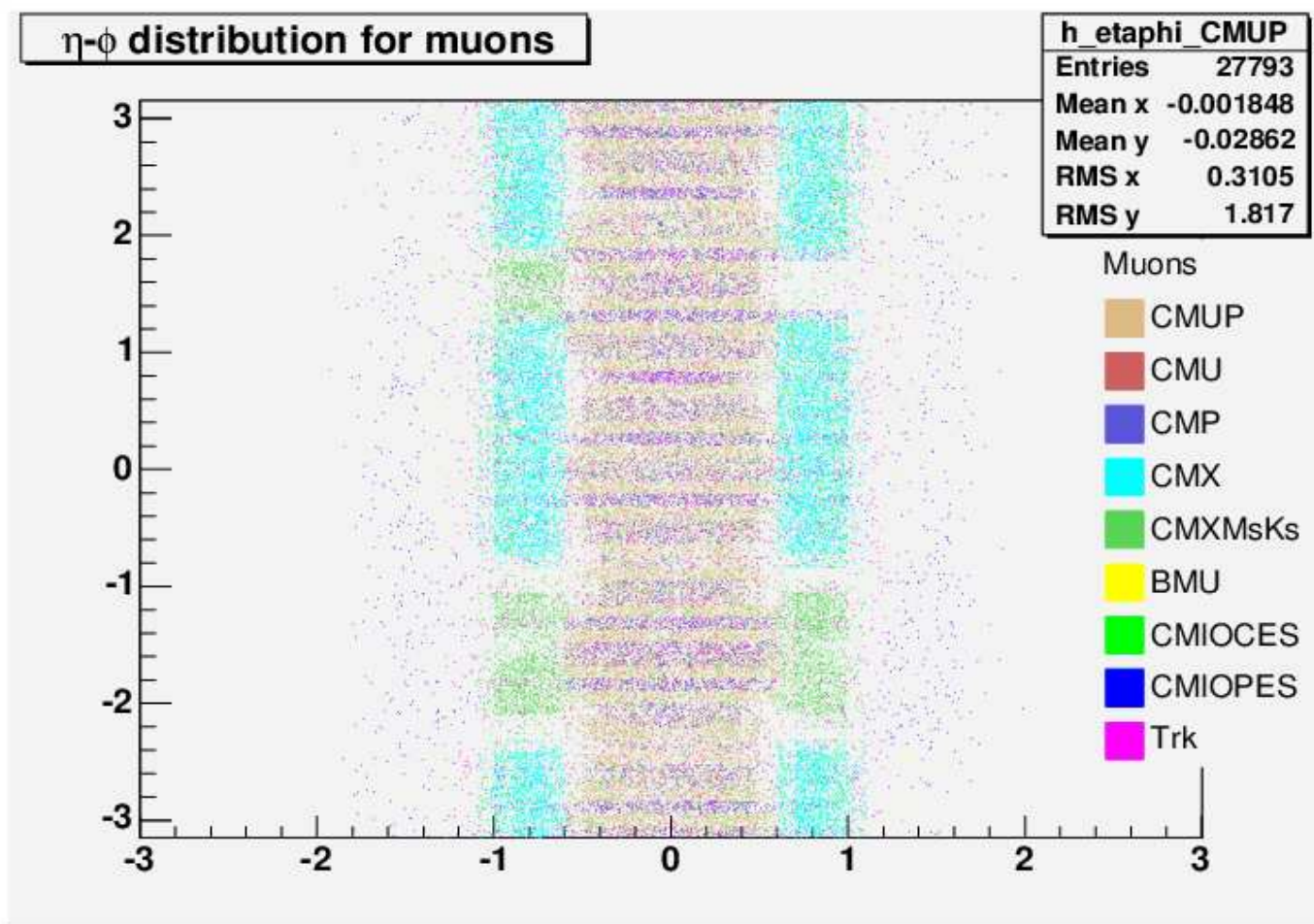
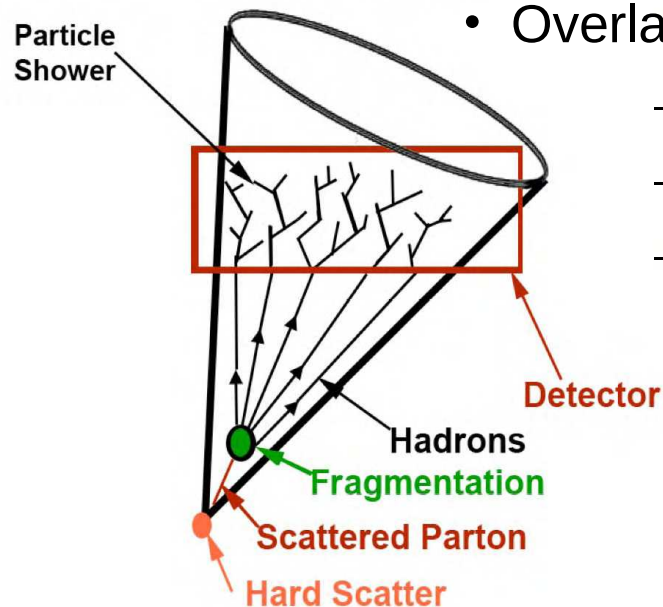


Figure 1: The η - ϕ coverage of all the muon categories used in this analysis.

Jet Identification

- Jets leave tracks in silicon and deposit energy in calorimeters
- JETCLU reconstructs the jet from its energy deposits
 - Find seed towers with $E_t > 1 \text{ GeV}$
 - Form preclusters of radius 0.5 in η - Φ space
 - Find E_t weighted center of cone, form clusters of radius 0.5 from towers with $E_t > 100 \text{ MeV}$
 - Iterate until tower list is unchanged
 - Ratcheting: Once added, towers are not removed
 - Overlap:
 - Total overlap: the smaller cluster is absorbed
 - Overlap > 0.75 : the clusters are combined
 - Overlap < 0.75 : the overlap is assigned to the closest center

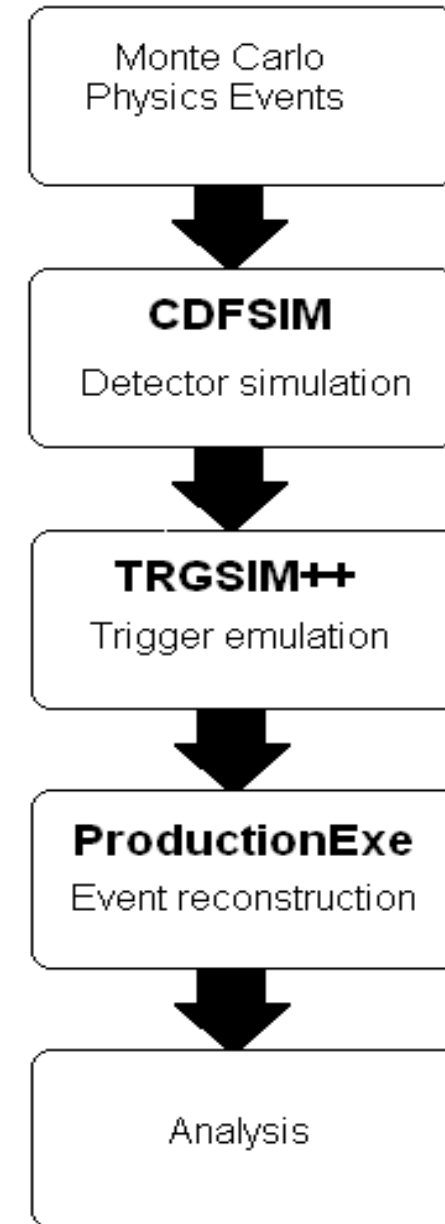


Generation of Physics Events

- Alpgen
 - Tree-level matrix element calculator
 - Emphasis on high jet multiplicities
 - Interface to Pythia for showering
 - Generates diboson and Drell-Yan events
- Pythia
 - Leading order MC
 - Used for $t\bar{t}$ and ggH events (Other higgs also?)
- W generated with Baur ME generator, passed to Pythia
- W +jets sample comes from data with fake leptons (not MC)

Detector Simulation, Event Reconstruction

- Monte Carlo events are passed to CDFSim
- Uses Geant 3, simulates CDF detector
- TRGSIM++ simulates trigger response
- ProductionExe reconstructs events
 - Identical to data reconstruction
- Passed to analysis code



Corrections to the Monte Carlo

$$\frac{\sigma \times \mathcal{B} \times \epsilon_{\text{filter}} \times \epsilon_i^{\text{trg}} \times s_i^{\text{lep}} \times \epsilon_{\text{vtx}} \times \mathcal{L}_i}{N_i^{\text{gen}}(|Z_0| < 60 \text{ cm})}$$

- σ : Cross section
- β : Branching fraction
- ϵ_{filter} : Filter efficiency
- ϵ^{trg} : Trigger efficiency
- s^{lep} : Lepton ID scale factor
- ϵ_{vtx} : Z vertex position requirement efficiency (run dependent)
- L: Luminosity of dataset (dependent on lepton category)
- N_{gen} : What is this?

Other corrections

- WW: rescaled to account for box diagrams
- ggH: reweighted to match HqT spectra

Systematic Uncertainties

Uncertainty Source	WW	WZ	ZZ	tt	DY	W γ	W+jet
Cross Section							
Total	6.0%	6.0%	6.0%	10.0%			
Acceptance							
Scale (jets)	-8.2%						
PDF Model (jets)	4.2%						
Higher-order Diagrams		10.0%	10.0%	10.0%		10.0%	
Jet Energy Scale	-14.8%	-12.9%	-12.1%	-1.7%	-29.2%	-22.0%	
W γ Modeling						10.0%	
b-tag Veto				3.2%			
Jet Fake Rates							28.0%
Luminosity	7.3%	7.3%	7.3%	7.3%	7.3%		

Uncertainty Source	$gg \rightarrow H$	WH	ZH	VBF
Cross Section				
Scale	67.5%			
PDF Model	29.7%			
Total		5.0%	5.0%	10.0%
Acceptance				
Scale (leptons)	3.1%			
Scale (jets)	-6.8%			
PDF Model (leptons)	4.8%			
PDF Model (jets)	-12.3%			
EWK Higher-order Diagrams		10.0%	10.0%	10.0%
Jet Energy Scale	-17.0%	-4.0%	-2.3%	-4.0%
Luminosity	7.3%	7.3%	7.3%	7.3%

- Because ggH and WW are dominant signal and background for combined analysis, they are treated more carefully
- Cross Section: Theoretical uncertainties
- Acceptance: Luminosity, higher order effects, trigger and lepton ID efficiencies

Validation

Which plots?