Search for the Standard Model Higgs in the Dilepton + Neutrino Final State at CDF II

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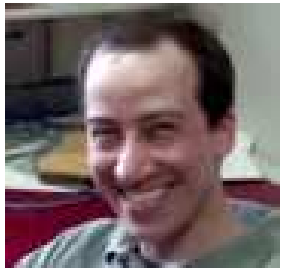
University of California, San Diego

Special HEP Seminar
Fermi National Accelerator Laboratory
Jan 22, 2008

My Great Teammates

Shih-Chieh Hsu



Elliot Lipeles

Matthew Norman

Rami Vanguri

Frank Würthwein

University of California, San Diego

Mark Neubauer

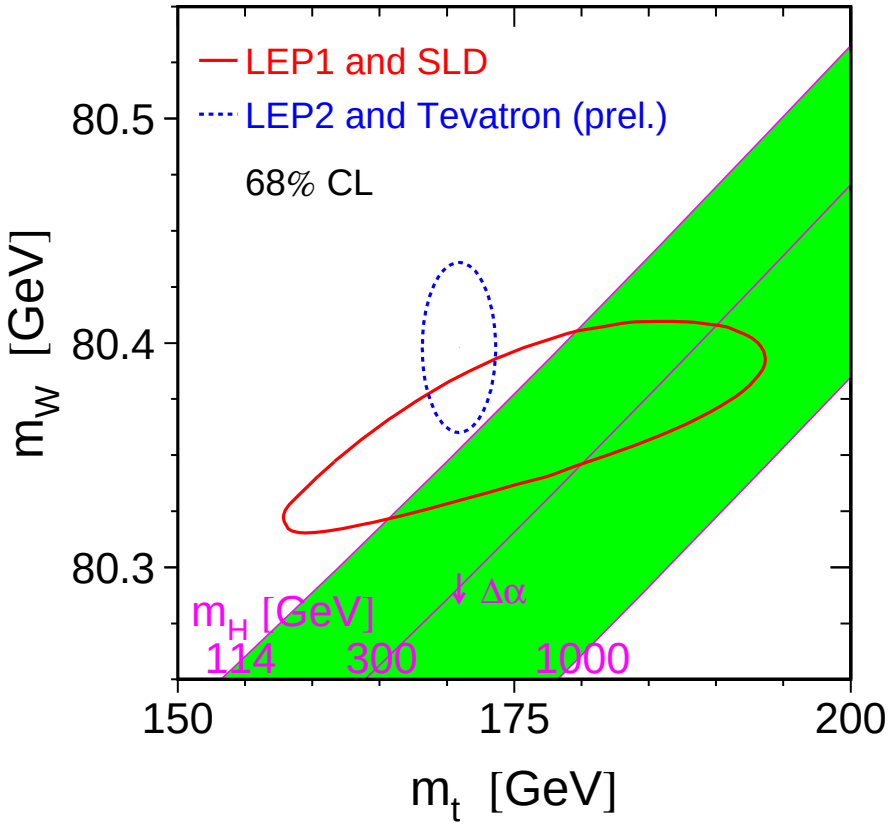
University of Illinois Urbana-Champaign

Outline

- Motivation
- Experimental Environment
- Event Selection and Sample Modeling
  - Lepton Coverage Improvement
  - Cross Check
- Multivariate Analysis
  - Event Discriminator with Matrix Element Method
  - Likelihood Ratio Cross Check
- Results
  - Latest results for $H \rightarrow WW$
  - Comparison to D0
- Summary

Why Higgs Particle?

- The consequence of the most ecnomic way of spontaneous electroweak symmetry breaking → Bosons acquire masses
- Have been searched for 30 years ...!?



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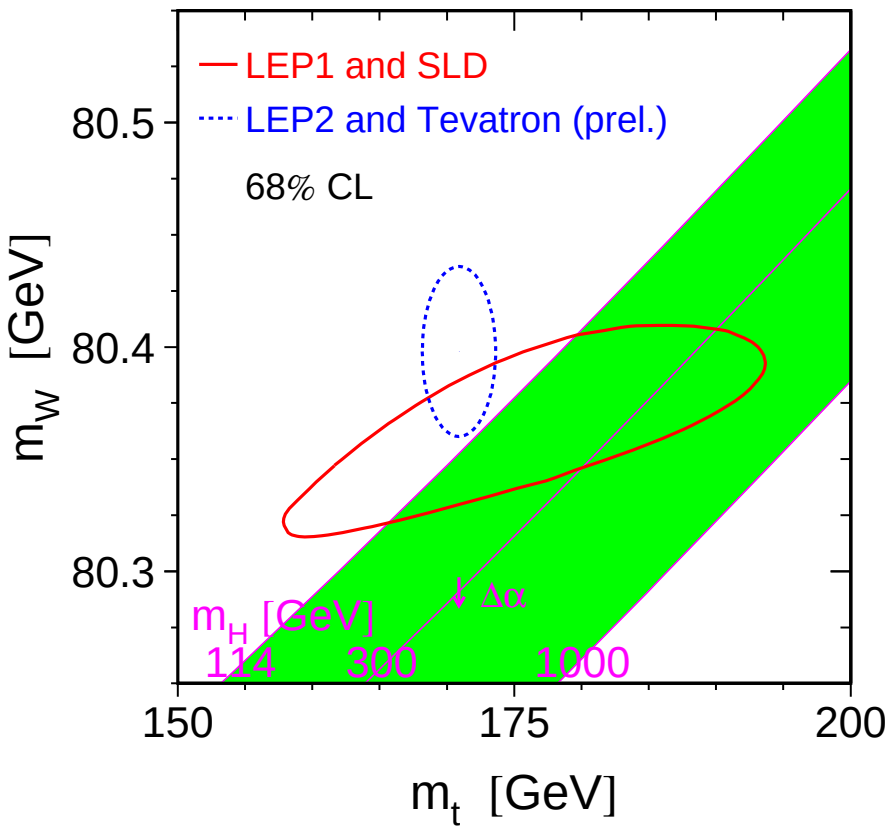
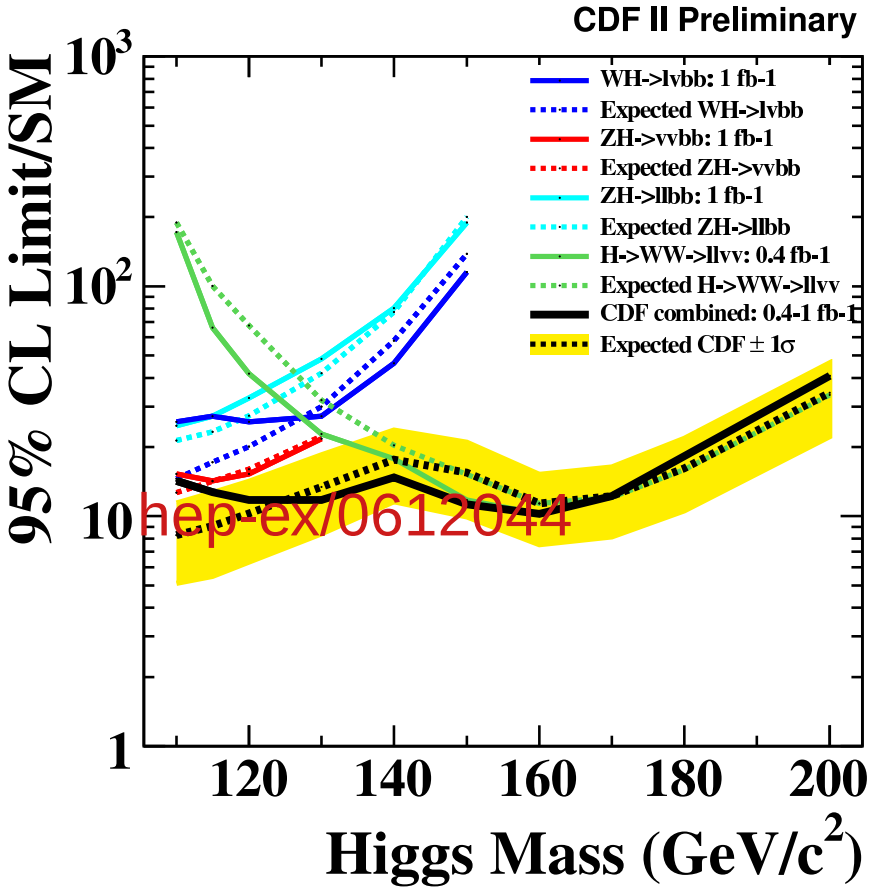
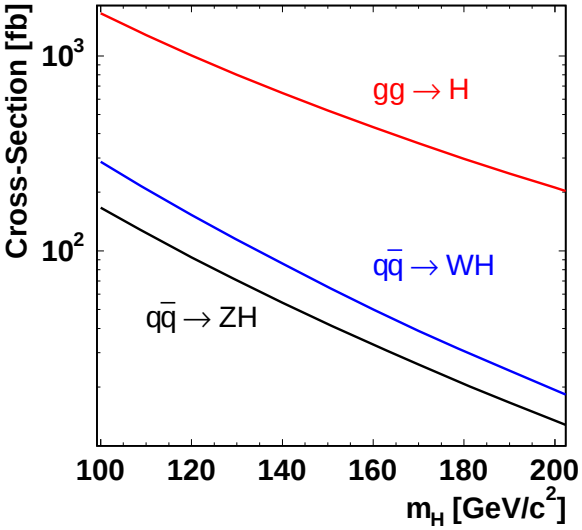




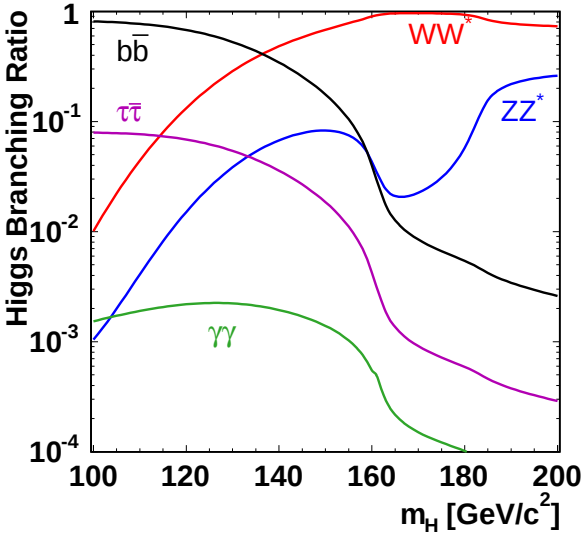
- Indirect limit prefer low m_H
- LEP limit $m_H > 114$ GeV/c^2

What We Know About Higgs?

- Higgs production cross section is calculated to Next-to-next-leading-order (NNLO)



$p\bar{p}$ Production



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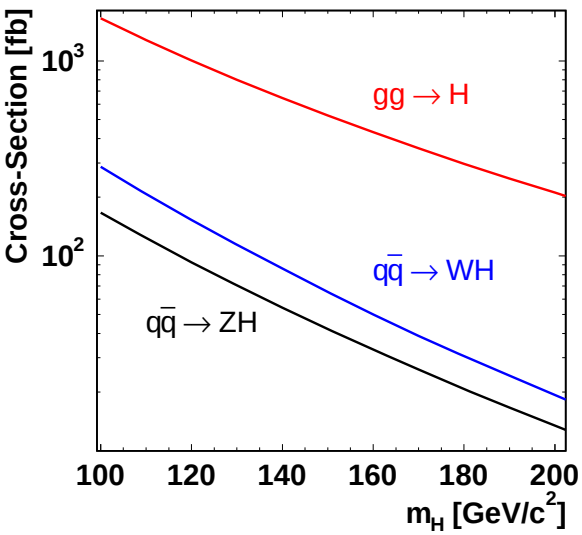

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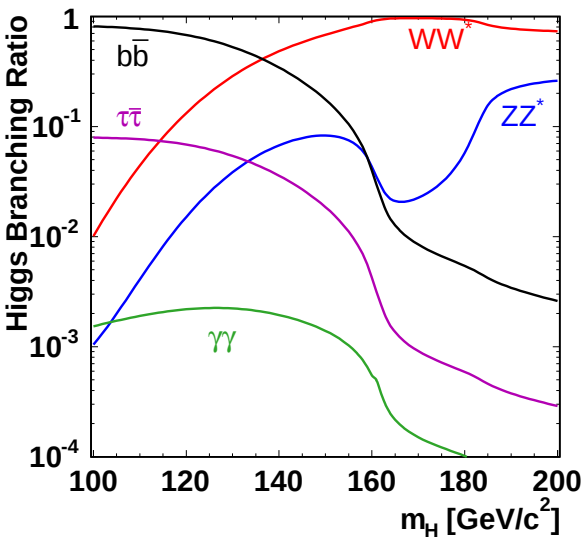

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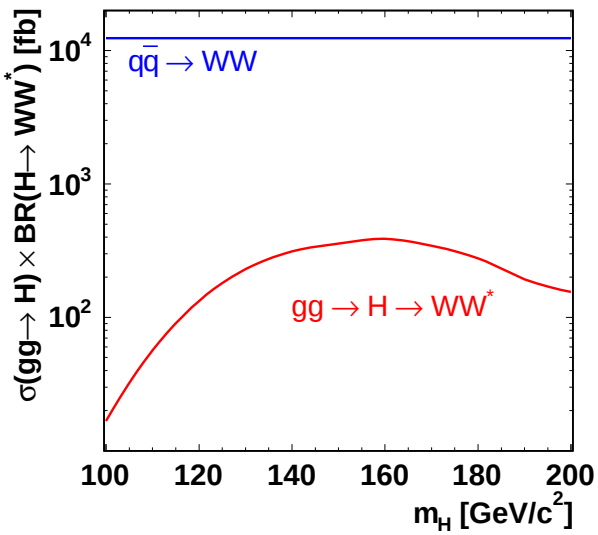
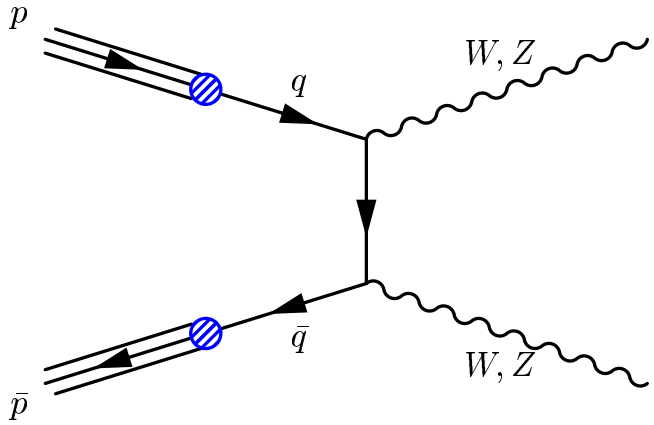
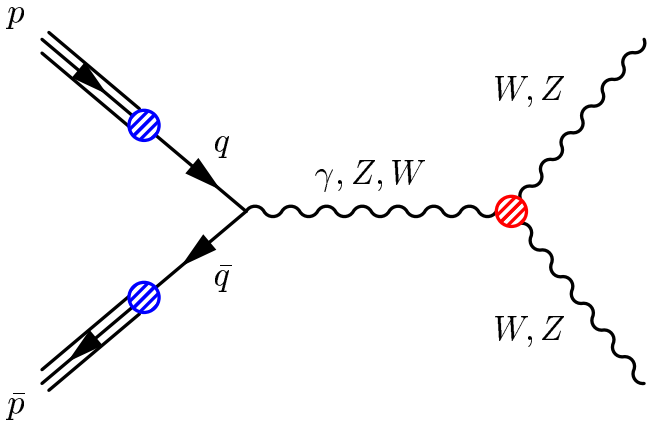


BR$\times$X-sec

Diboson Physics Outlook

- Access to the Gauge Boson Self-Couplings





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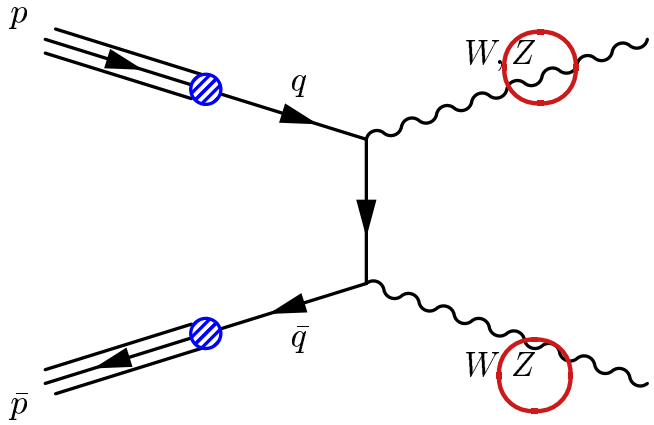

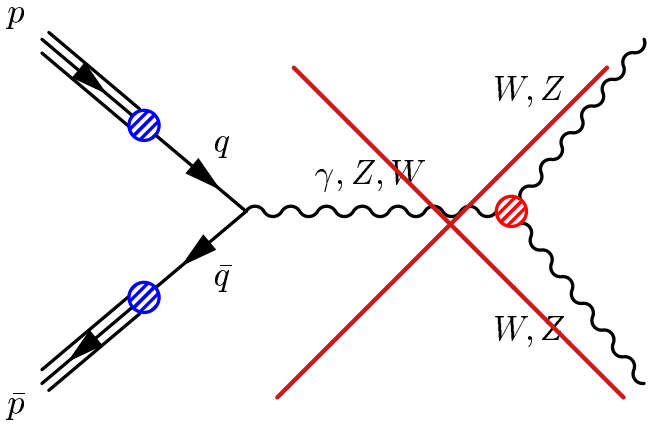

No s-channel for *ZZ*

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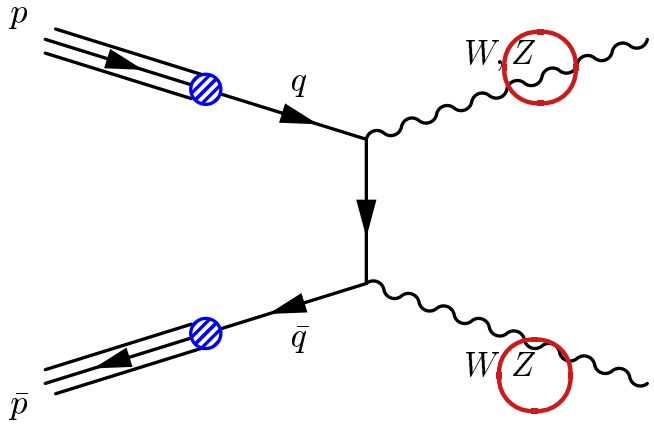

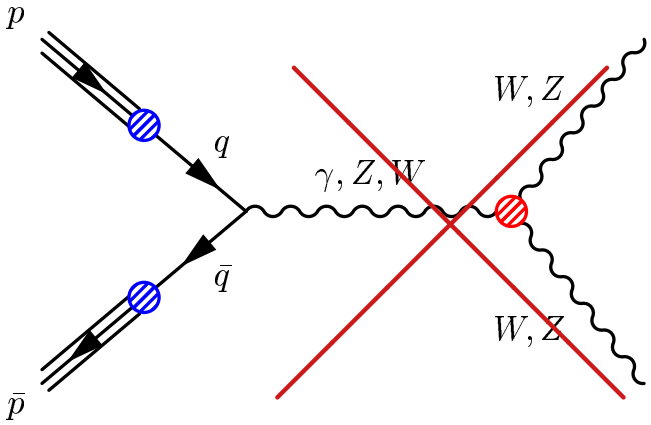

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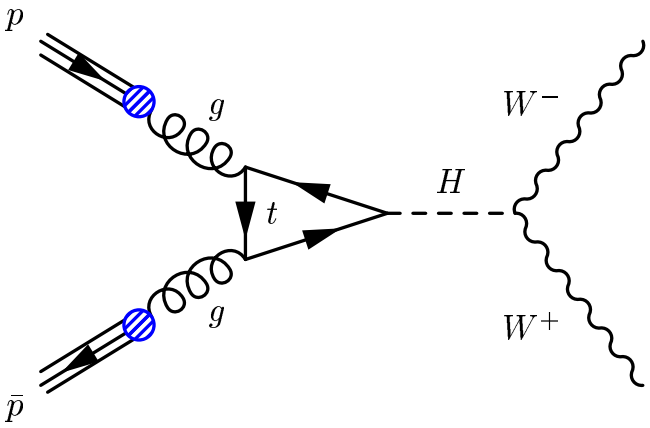

Searching for the Standard Model Higgs

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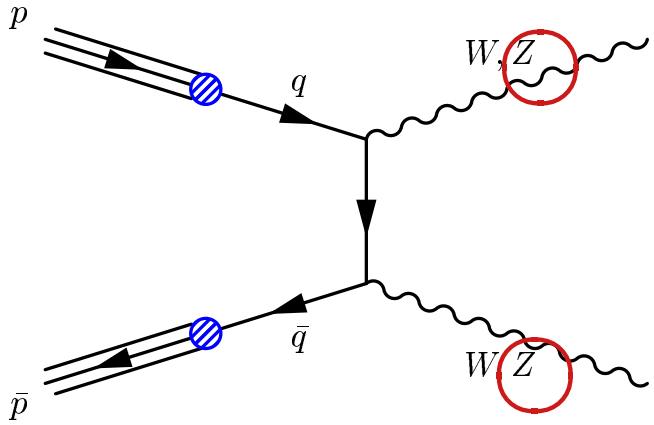

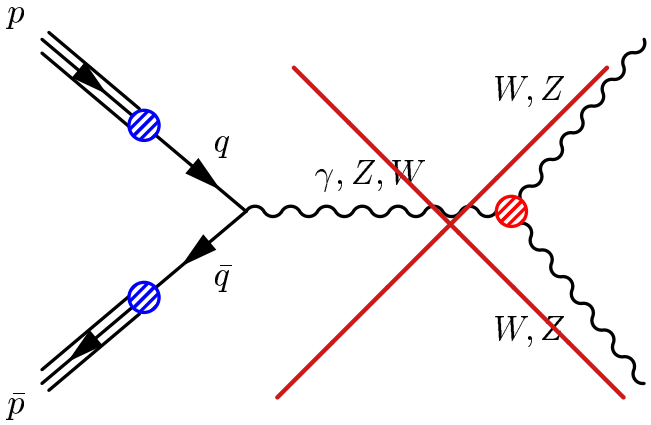

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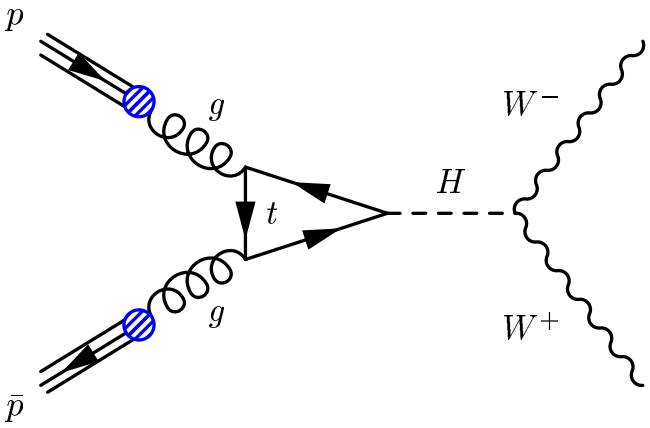
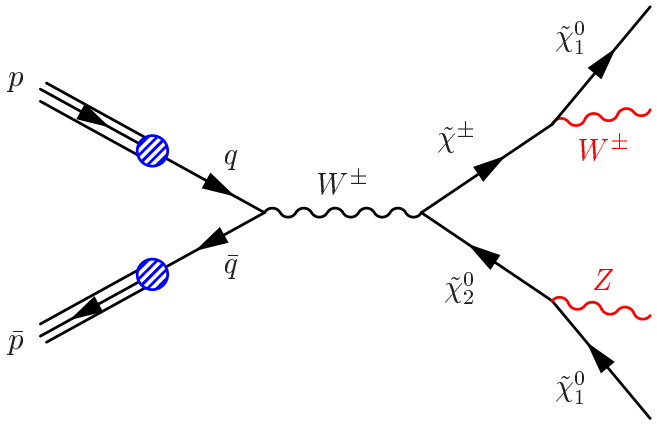
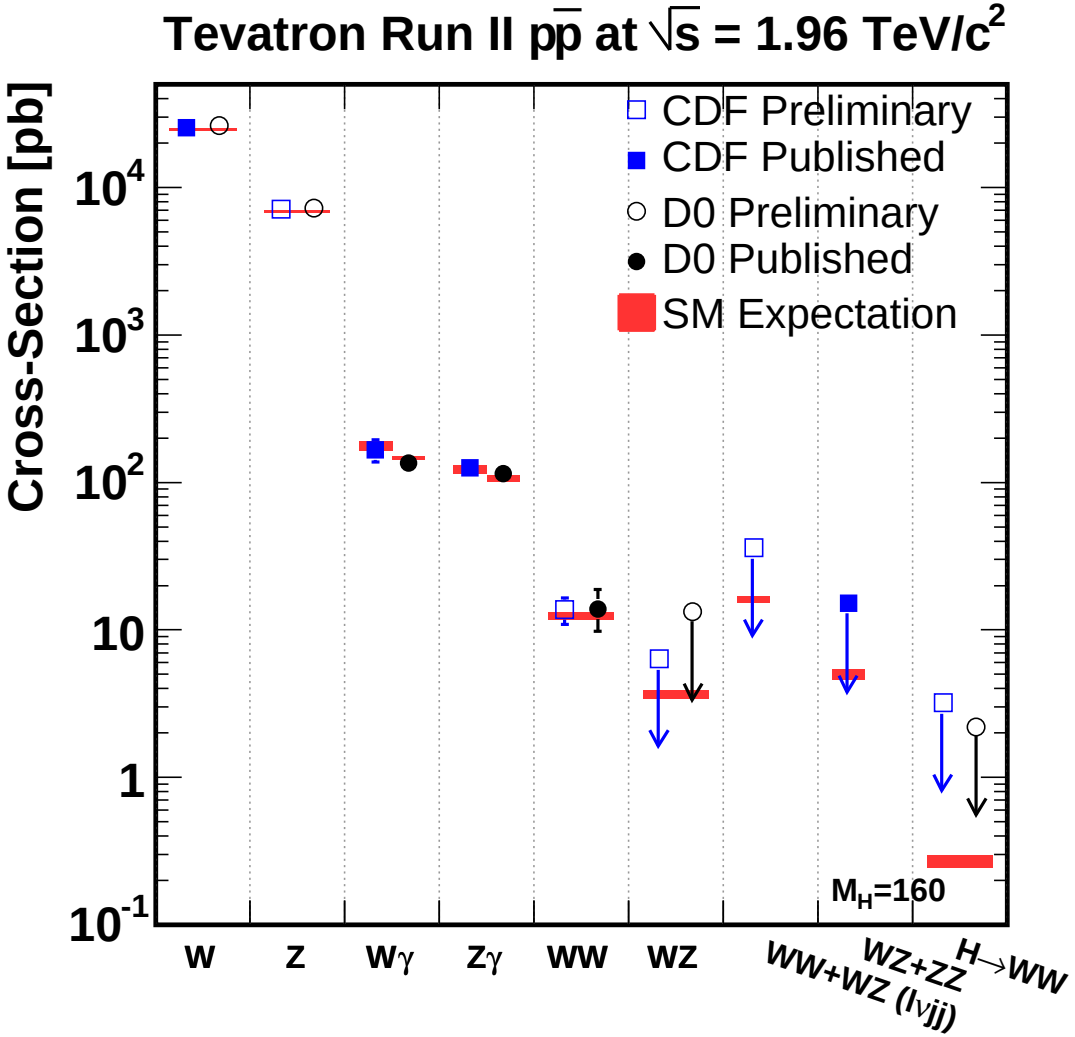


- Searching for new physics



Searching for the Standard Model Higgs

Large Backgrounds And Small Signal



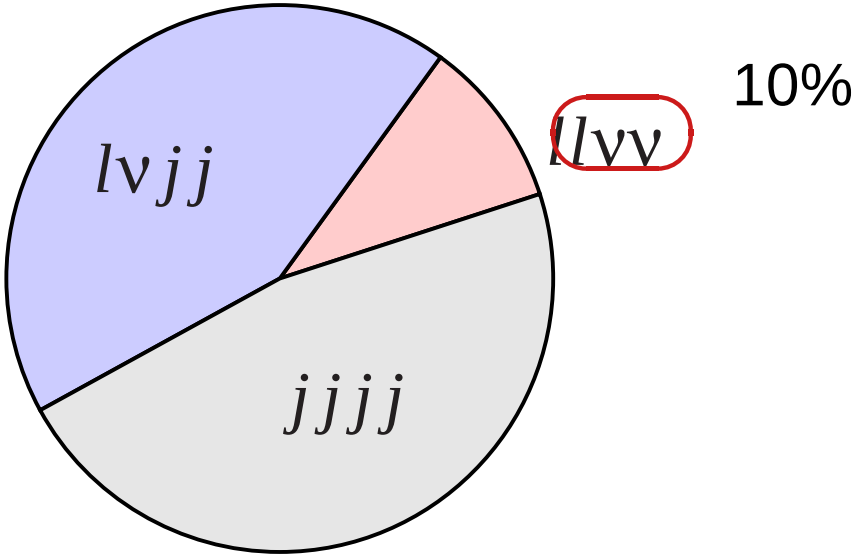
Extremely rare process

- O(10^9) multi-jets QCD
- O(10^4) Drell-Yan process
- O(10^2) irreducible contamination: continuum *WW*

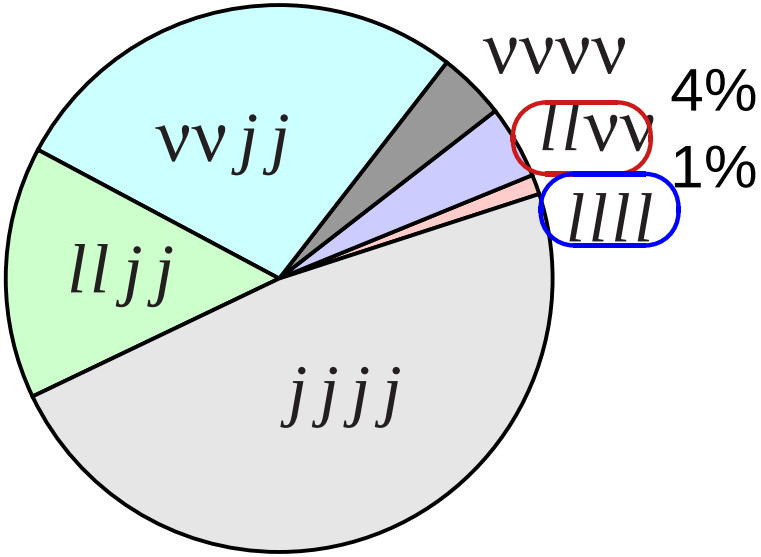
Missing Information

- neutrino doesn't interact with detector
- high P_T ν cause large imbalance transverse energy $\vec{\not{E}}_T = -\Sigma\vec{E}_T$

Why Dilepton+Neutrino Final State?



WW and $H \rightarrow WW$



ZZ

l includes τ

Fully Leptonic

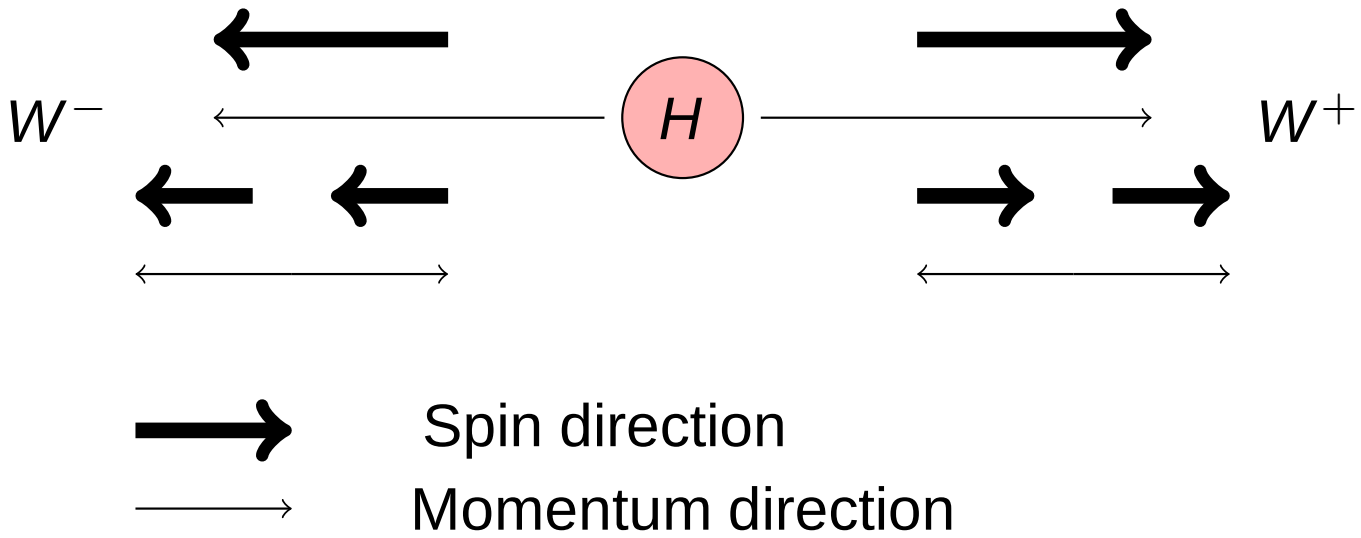
- Small branching fractions
- Low backgrounds
- Controlable backgrounds

Semileptonic

- $\approx 5 - 10\times$ branching fractions
- $\approx 1000\times$ backgrounds
- Complicated detector and nonperturbative physics in backgrounds

Unique Kinematics Signature

- Spin 0 Physics to discriminate $H \rightarrow WW^*$ from $p\bar{p} \rightarrow WW^*$



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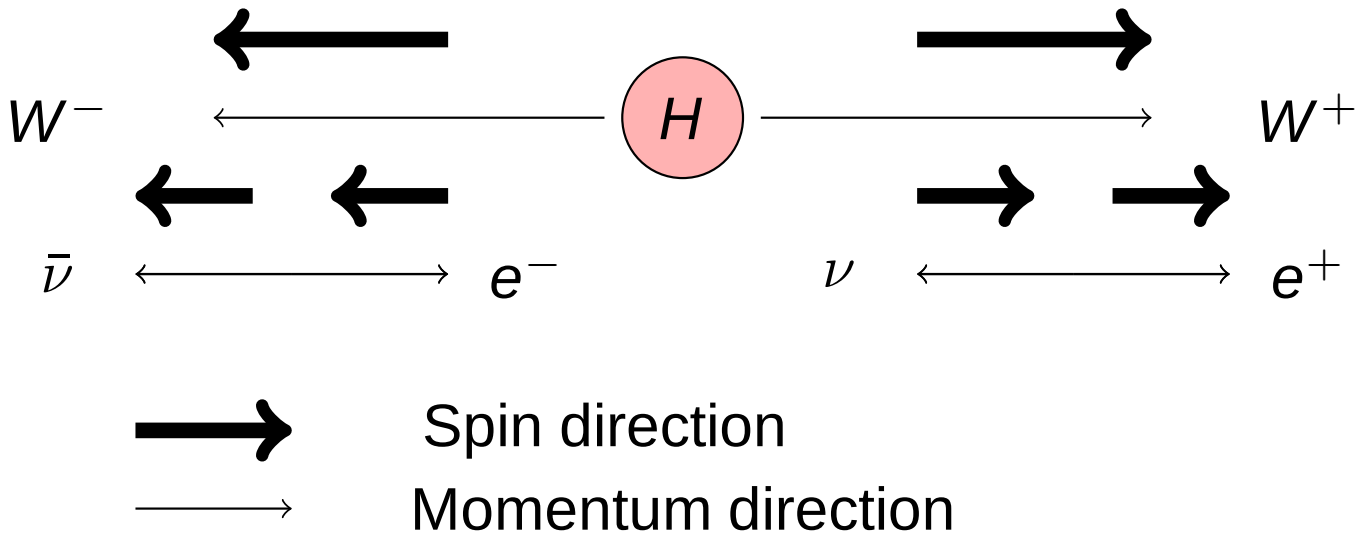
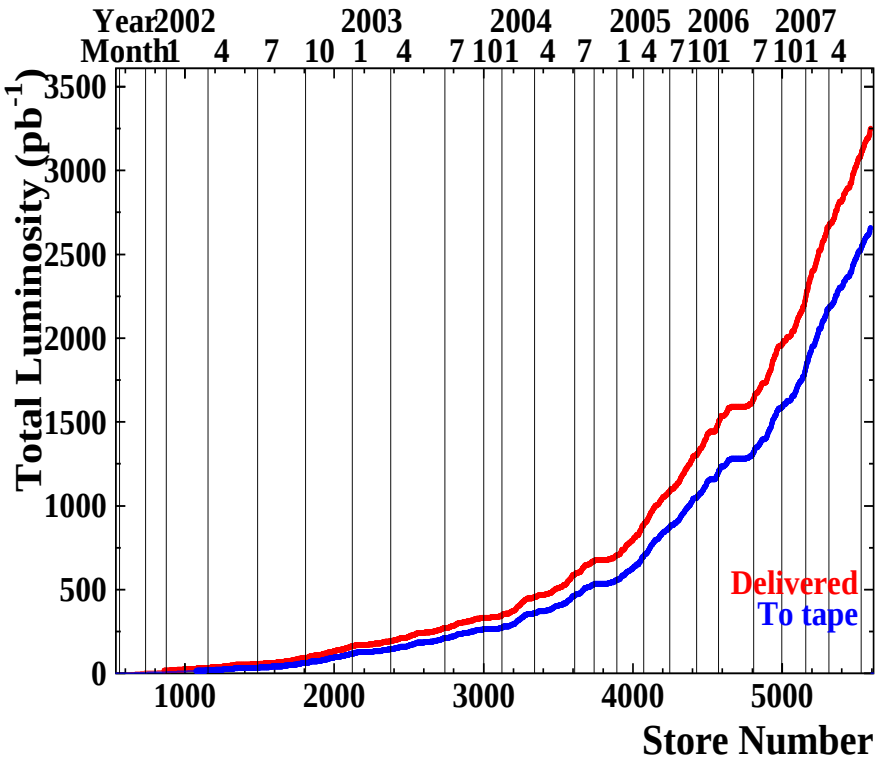
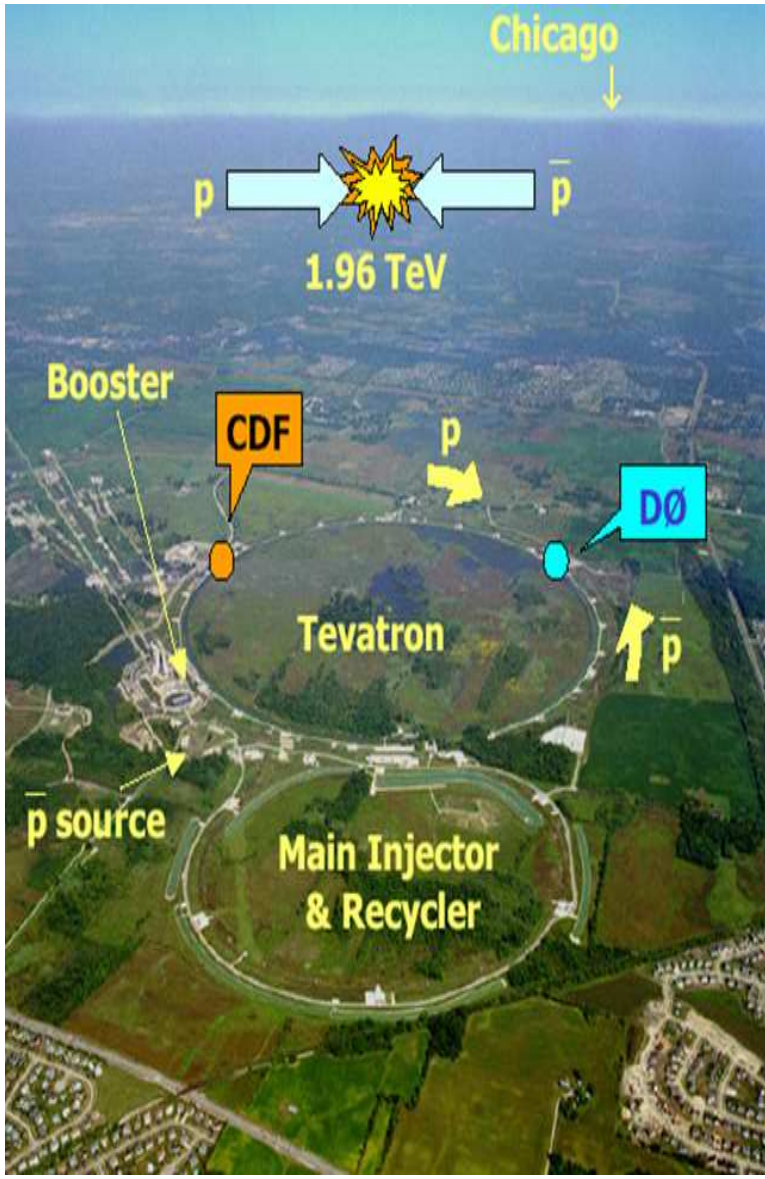


dilepton decayed from Higgs tend to point to the same direction

Experiment Environment

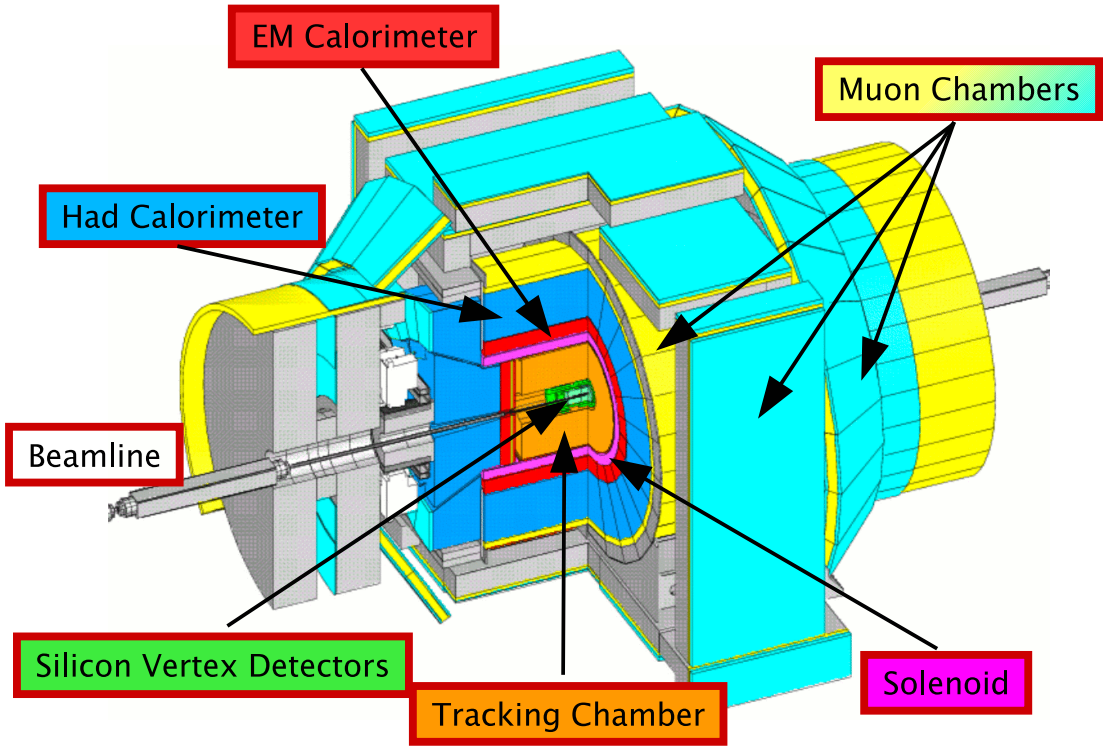
- Reached target luminosity $2x10^{32} cm^{-2} s^{-1}$ in the end of 2006
- $\sim$1.5 Pile up events at this luminosity
- Expect to have 6 to 8 fb^{-1} in 2010
- Used 1.9 fb^{-1} for this analysis





CDF II

- η coverage 2.5 for showers and 1.5 for tracks
- 1 GeV/c p_T resolution for 45 GeV/c lepton
  - electron 13% $\sqrt{E_T}$
  - muon 0.05% p_T^2
- 5 GeV $\not{E}_T$ resolution for 60 GeV ΣE_T
  - 64%$\sqrt{\Sigma E_T}$



Analysis Strategy

Event Signatures

- two leptons - e or μ
- larger transverse energy imbalance $\not{E}_T$
- low multiplicity of jets

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- Monte Carlo + Data driven estimation
- Cross check sample modeling
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- two leptons - e or μ
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Model each background

- Monte Carlo + Data driven estimation
- Cross check sample modeling
- Extract signal yields by fitting

How to achieve observation?

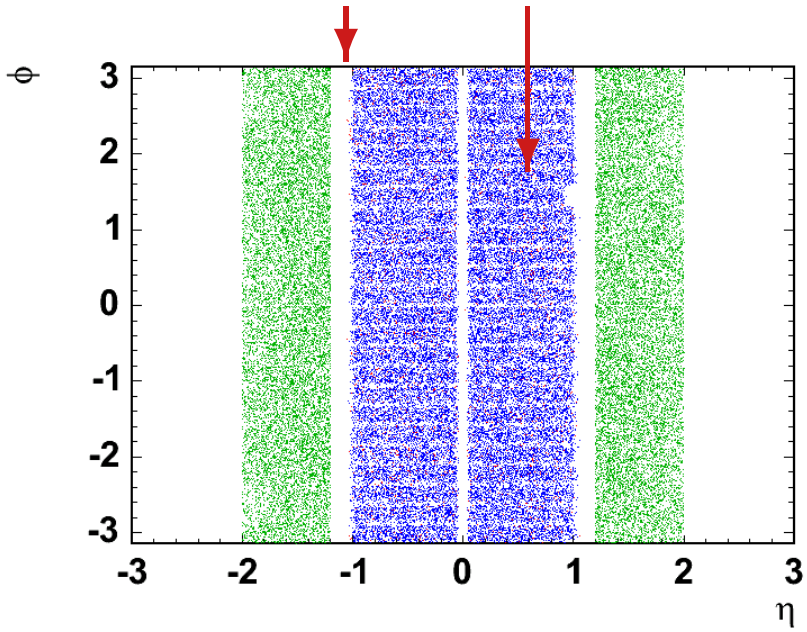
- Increase signal acceptance but suppress major backgrounds
- Use all available kinematic information to discriminate signal from irreducible backgrounds

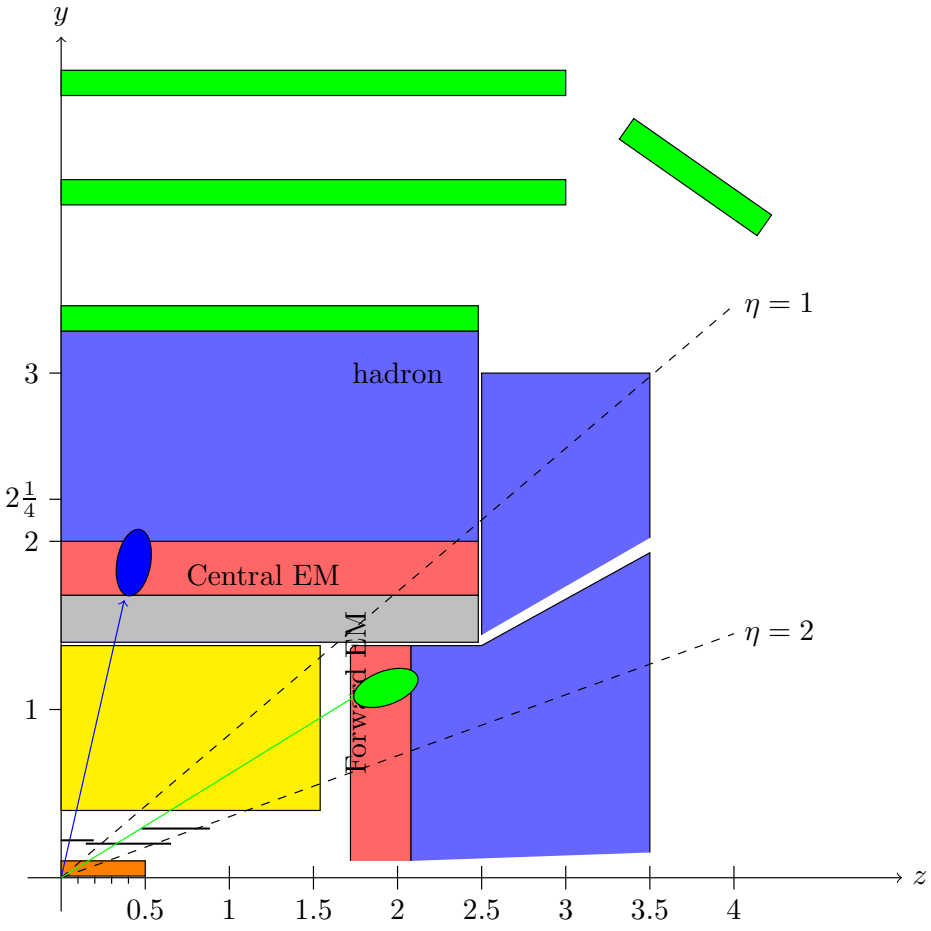
Maximizing the acceptance part I: leptons

- Aim to use every track and electromagnetic shower found

Electrons in Winter 2006 Analysis

- Cracks in η and ϕ

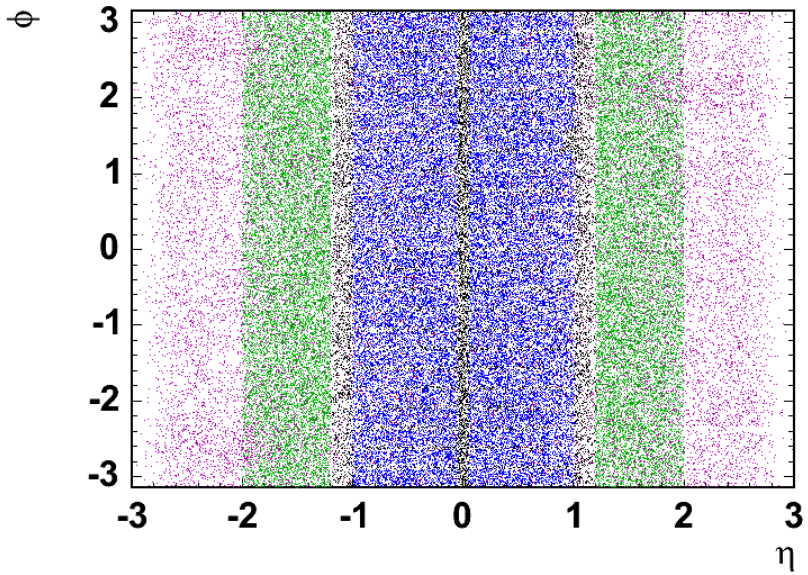


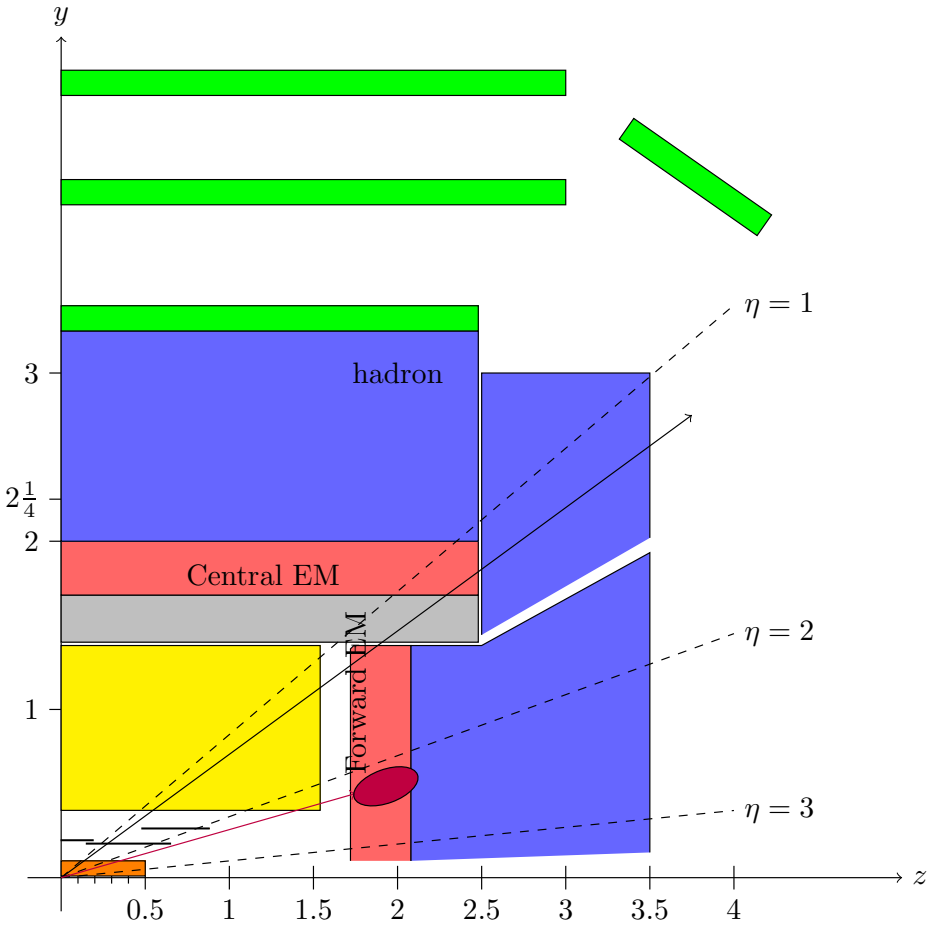


Add New Electrons

Electrons used in Fall 2006 Analysis

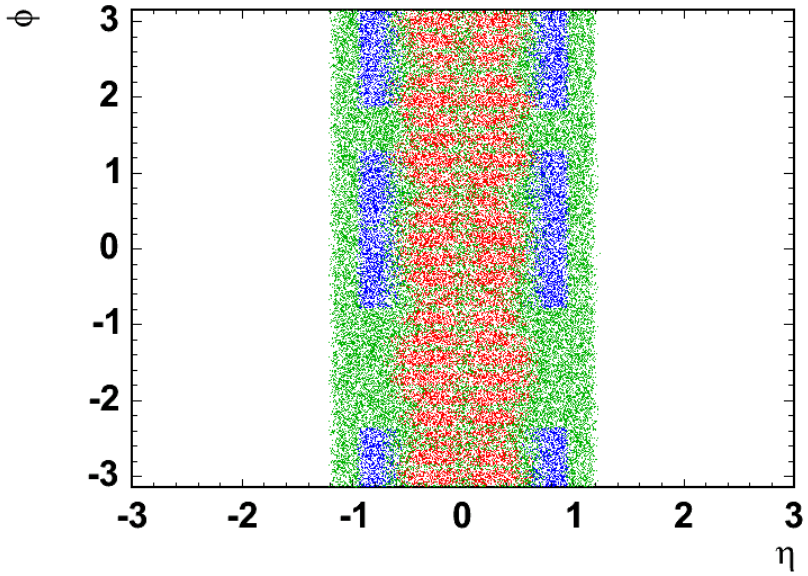
- Use tracks in cracks
- Use forward showers (only for $WZ \rightarrow 3l\nu/ZZ \rightarrow 4l$)

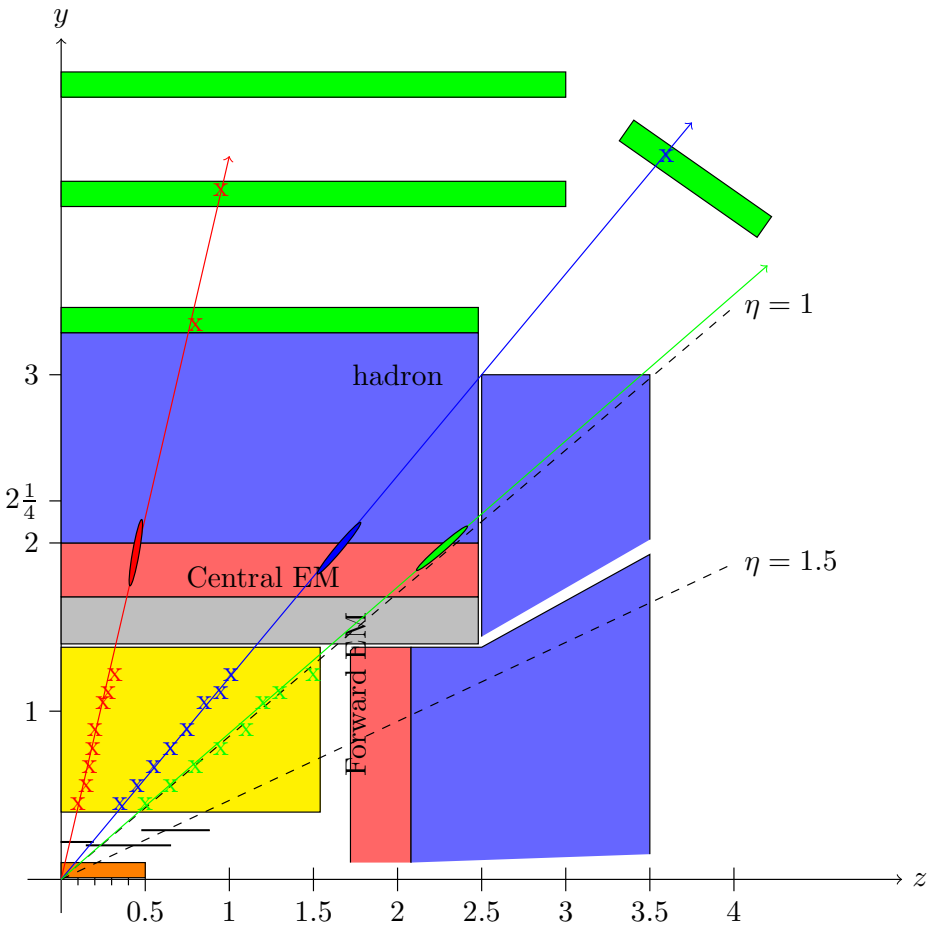




Muons in Winter 2006 Analysis

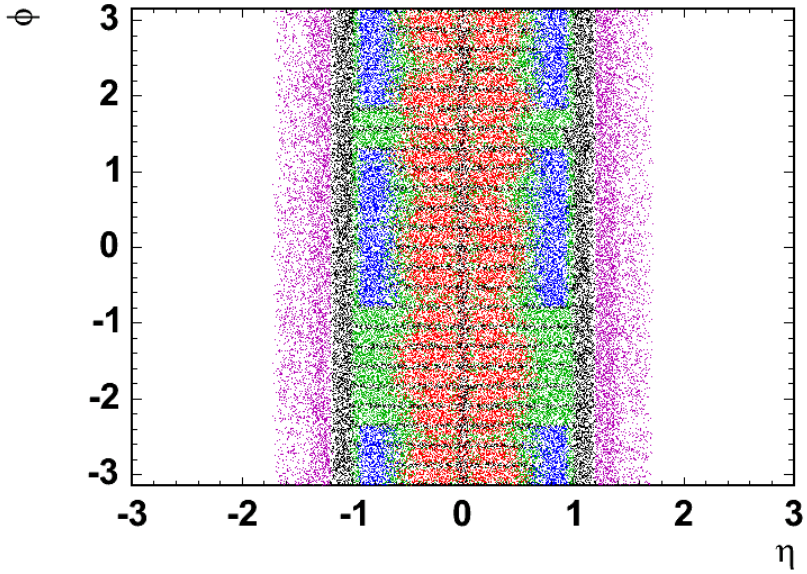
- Require minimum-ionizing particles (MIPs)

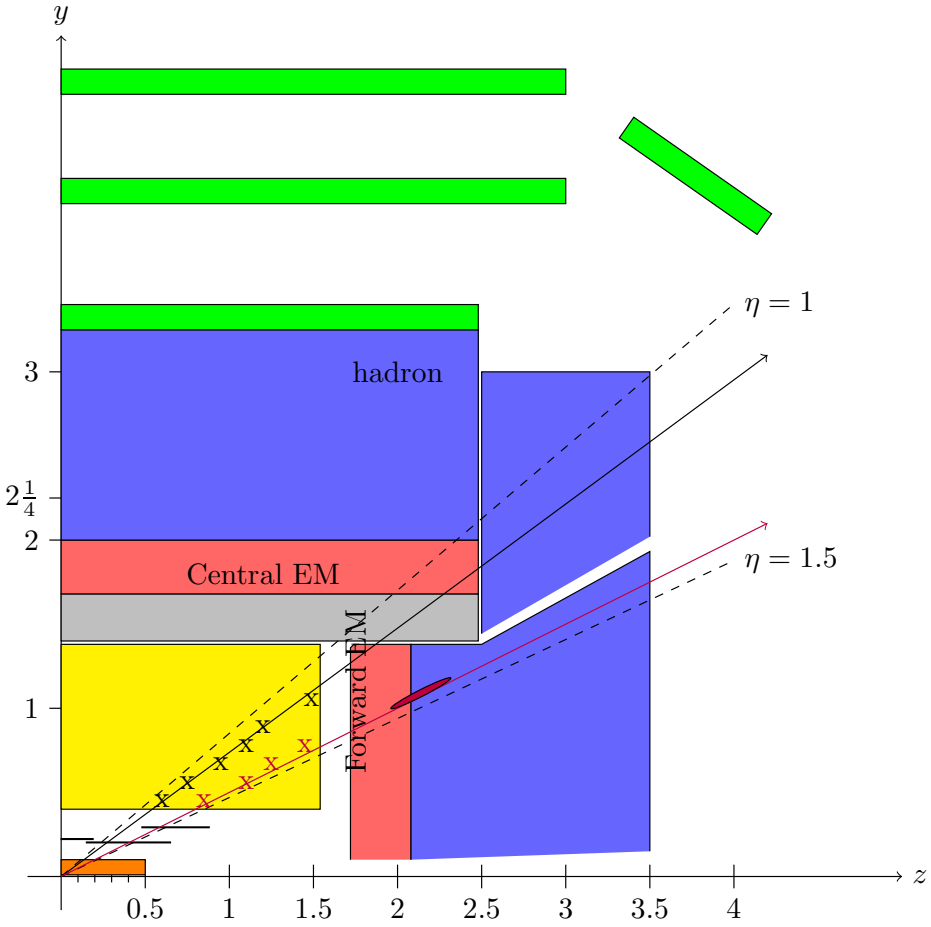




Adding New Muons

- Use crack tracks
- Use forward tracks which is consistent with MIPs

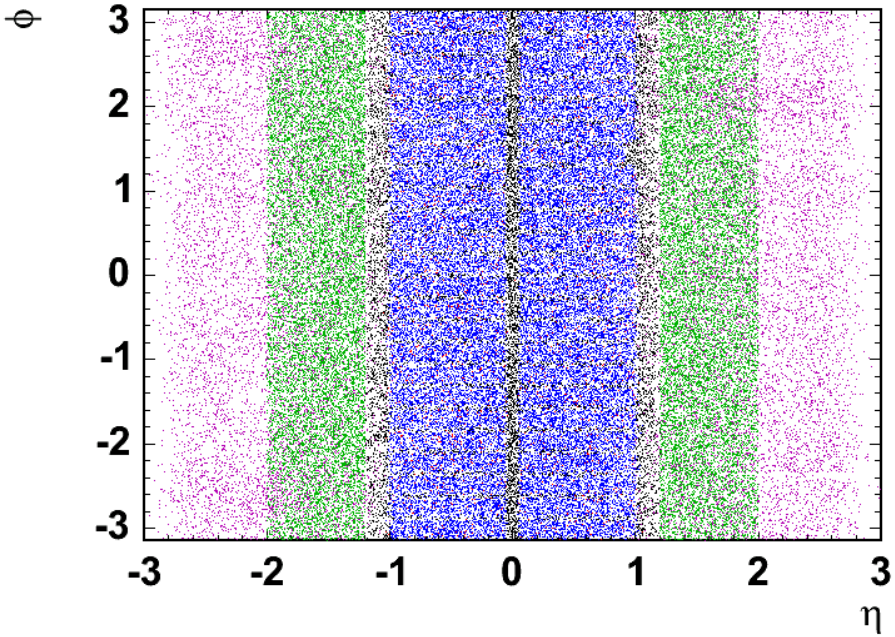




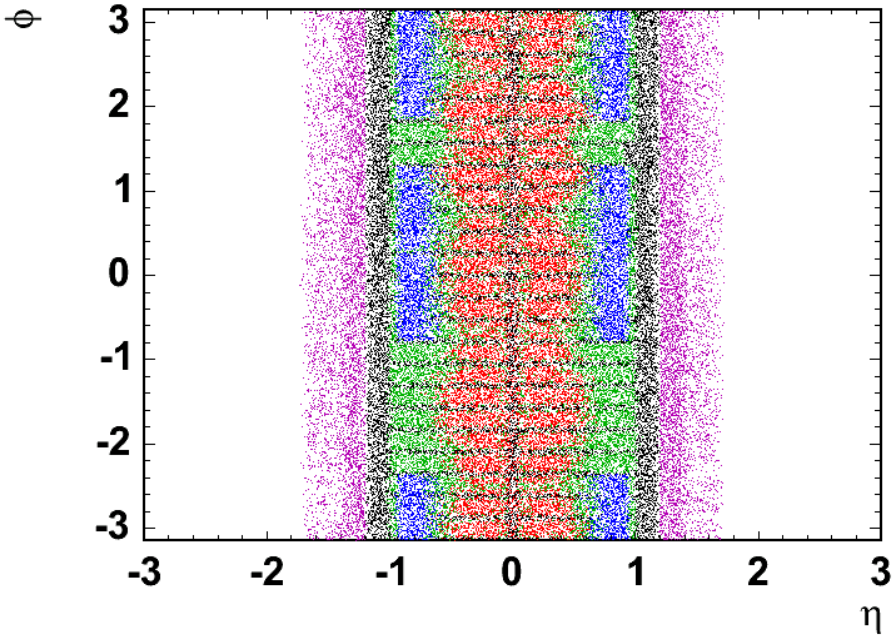
The Improved Acceptance

Lepton Types used in Fall 2006 Analysis

electron



muon



- $WZ \rightarrow 3l\nu$ gains 100% $\rightarrow 6\sigma$ observation
- $ZZ \rightarrow 4l$ gains 250%
- Higgs, $WW, ZZ \rightarrow 2l\nu\nu$ gains about 50%
  Backgrounds in $ll\nu\nu$ increase 30% to 80%

Maximizing the acceptance part II: Event Selection

- Make kinematic cuts as loose as possible

Event Selection Overview

Background in dilepton + $\not{E}_T$

Source	N_{gen}
Drell-Yan$^a \rightarrow ll$	1.0×10^7
W+jets^b	2.1×10^6
$W\gamma^c \rightarrow l\nu\gamma$	1.1×10^5
$t\bar{t} \rightarrow bbll\nu\nu$	1.3×10^3
$WZ^a \rightarrow 3l\nu$	2.1×10^2
$ZZ^a \rightarrow ll\nu\nu$	1.3×10^2
$WW \rightarrow ll\nu\nu$	2.4×10^3

a $M_Z > 15$ GeV/c^2
b $\Delta R(j,j) > 0.4$, $P_T(j) > 15$ GeV/c, $|\eta(j)| < 3$
c $\Delta R(l,\gamma) > 0.35$, $P_T(l)$, $P_T(\gamma) > 8$ GeV/c

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- Two and only two leptons
- $p_T > 20, 10$ GeV/c
- $m_{ll} > 16$ GeV/c^2

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- $p_T > 20, 10$ GeV/c
- $m_{ll} > 16$ GeV/c^2
- $\not{E}_{T\,\mathrm{spec}} > 25GeV$ (15 when eμ)
  $\not{E}_{T\,\mathrm{spec}} =$
  - $\not{E}_T, \Delta\phi > \pi/2$
  - $\not{E}_T sin(\Delta\phi), \Delta\phi < \pi/2$

  , where $\Delta\phi$(nearest l or j)

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- Opposite sign charge

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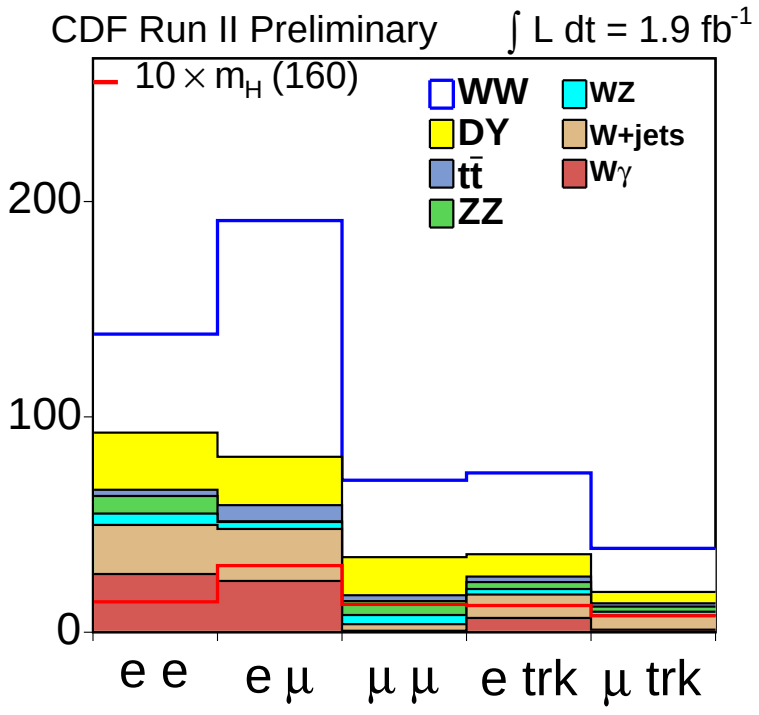
- $p_T > 20, 10$ GeV/c
- $m_{ll} > 16$ GeV/c^2
- $\not\!\!E_{T\,\mathrm{spec}} > 25GeV$ (15 when eμ)
  $\not\!\!E_{T\,\mathrm{spec}} =$
  - $\not\!\!E_T, \Delta\phi > \pi/2$
  - $\not\!\!E_T sin(\Delta\phi), \Delta\phi < \pi/2$

  , where $\Delta\phi$(nearest l or j)
- Opposite sign charge
- Njets < 2
  $E_T(jet) > 15$ GeV, $|\eta| < 2.5$

Expected Yields

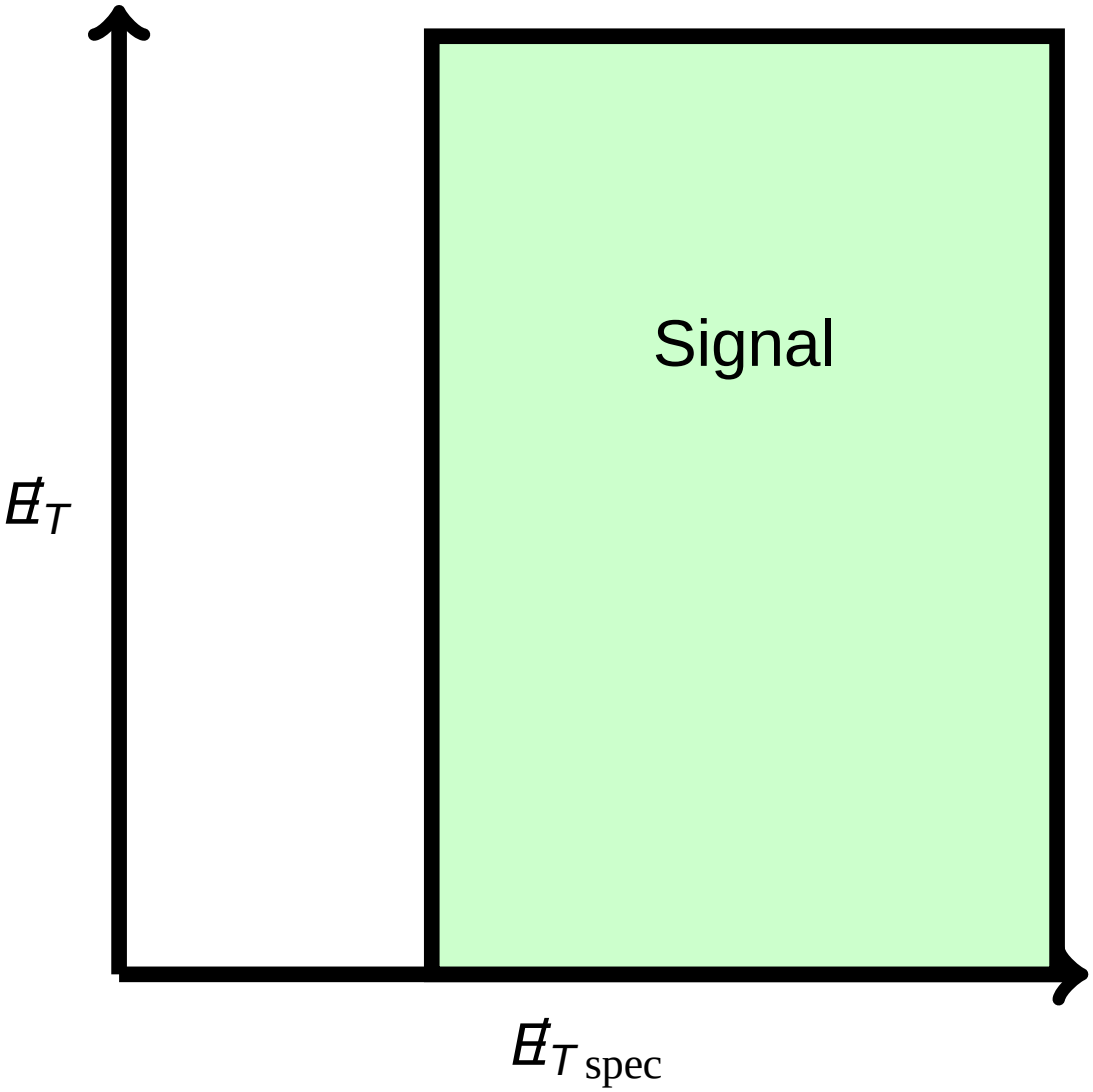
Source	N_{gen} 1.9 fb^{-1}	N_{exp}
Drell-Yan	1.0×10^7	82 ± 16
W+jets	2.1×10^6	67 ± 14
$W\gamma$	1.1×10^5	59 ± 12
$t\bar{t}$	1.3×10^3	17 ± 13
WZ	2.1×10^2	17 ± 3
ZZ	1.3×10^2	21 ± 3
WW	2.4×10^3	251 ± 36
Sum		513 ± 41



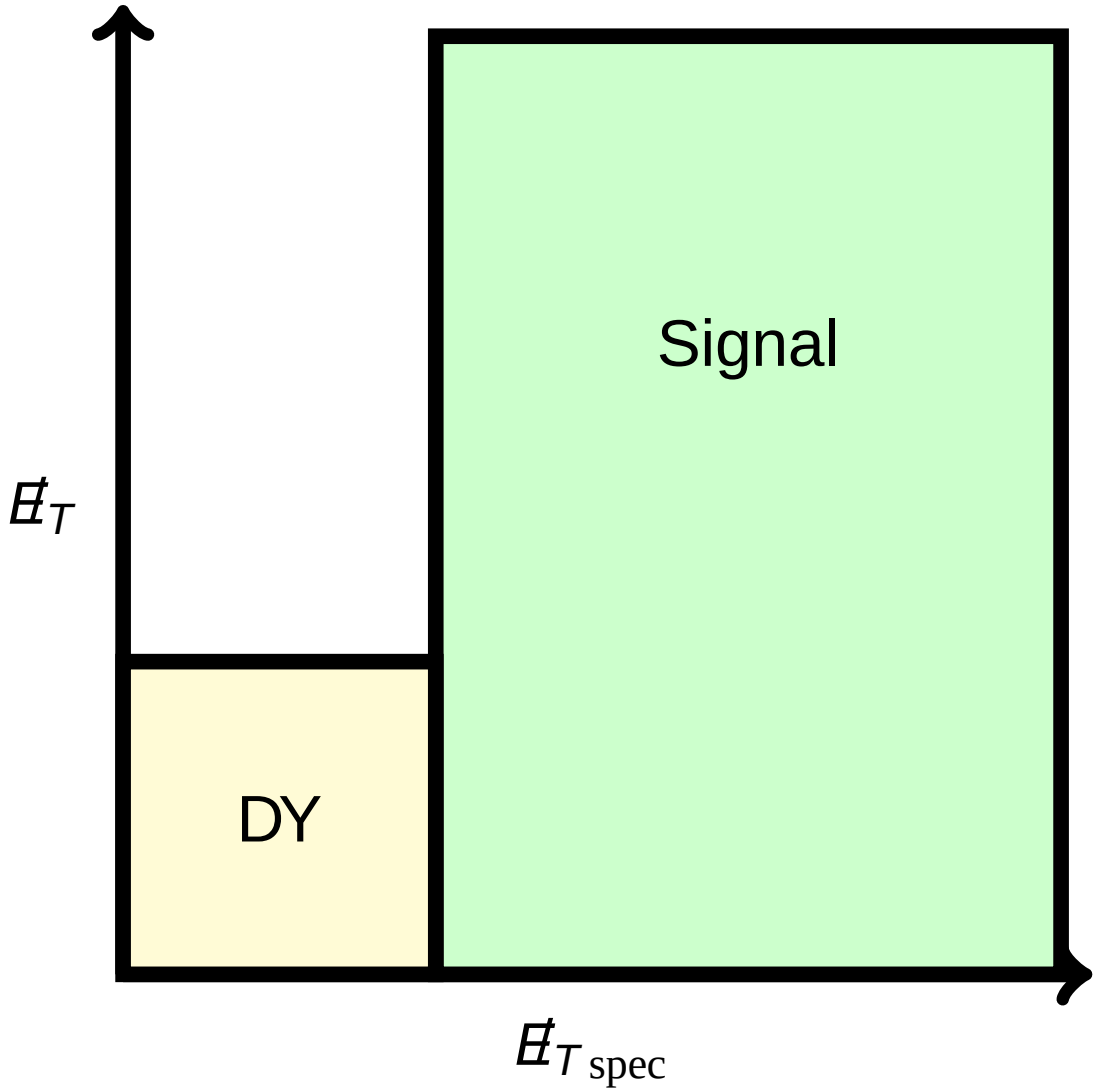
Predicted Higgs Yields

Higgs Mass (GeV/c^2)									
110	120	130	140	150	160	170	180	190	200
0.4	1.3	3.0	4.8	6.4	7.8	7.6	6.2	4.4	4.5

Cross check



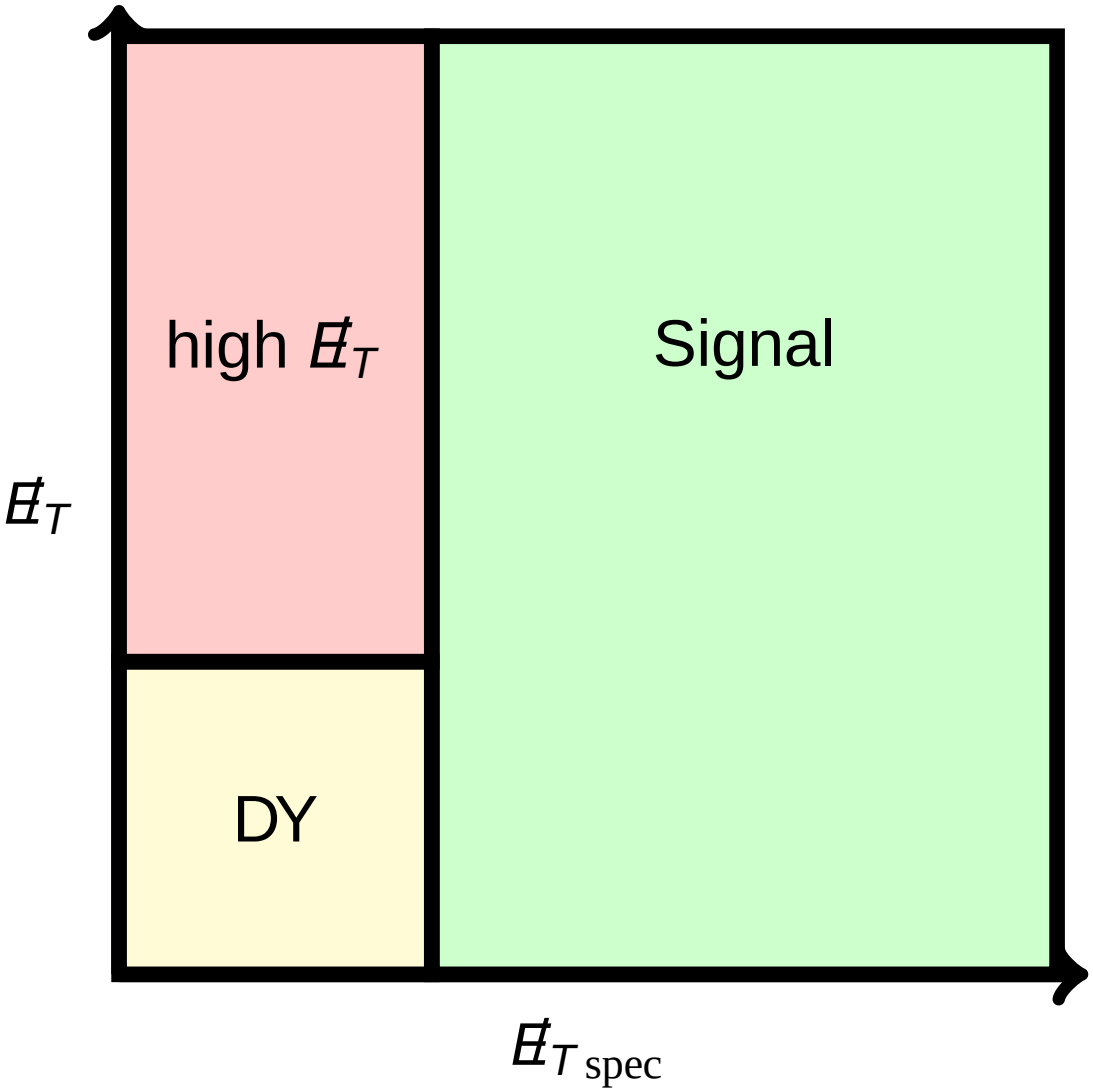
Cross check



DY

test lepton ID and trigger

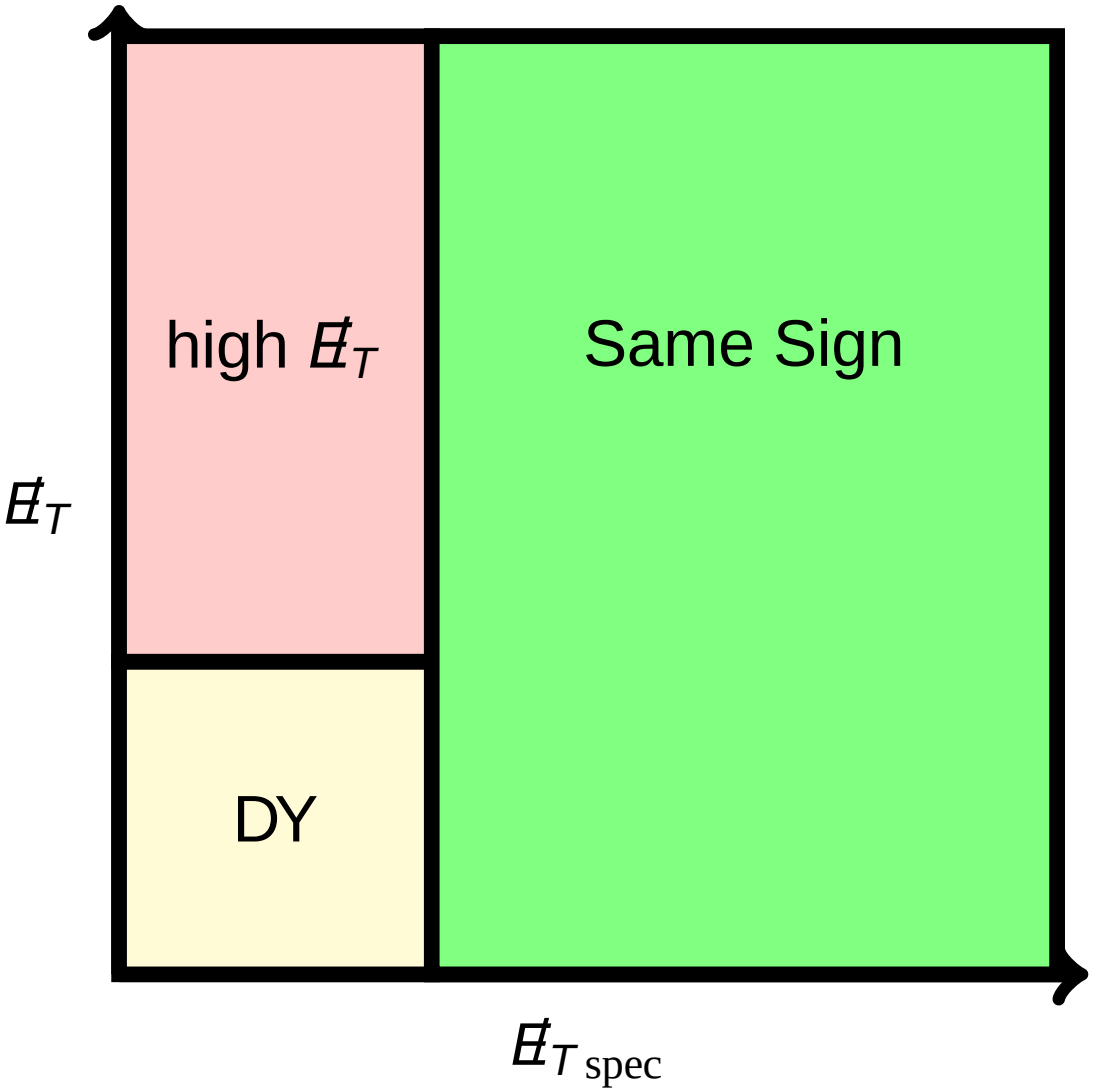
Cross check



DY
test lepton ID and trigger

high $\not{E}_T$
test lepton mis-measurem

Cross check



DY

test lepton ID and trigger

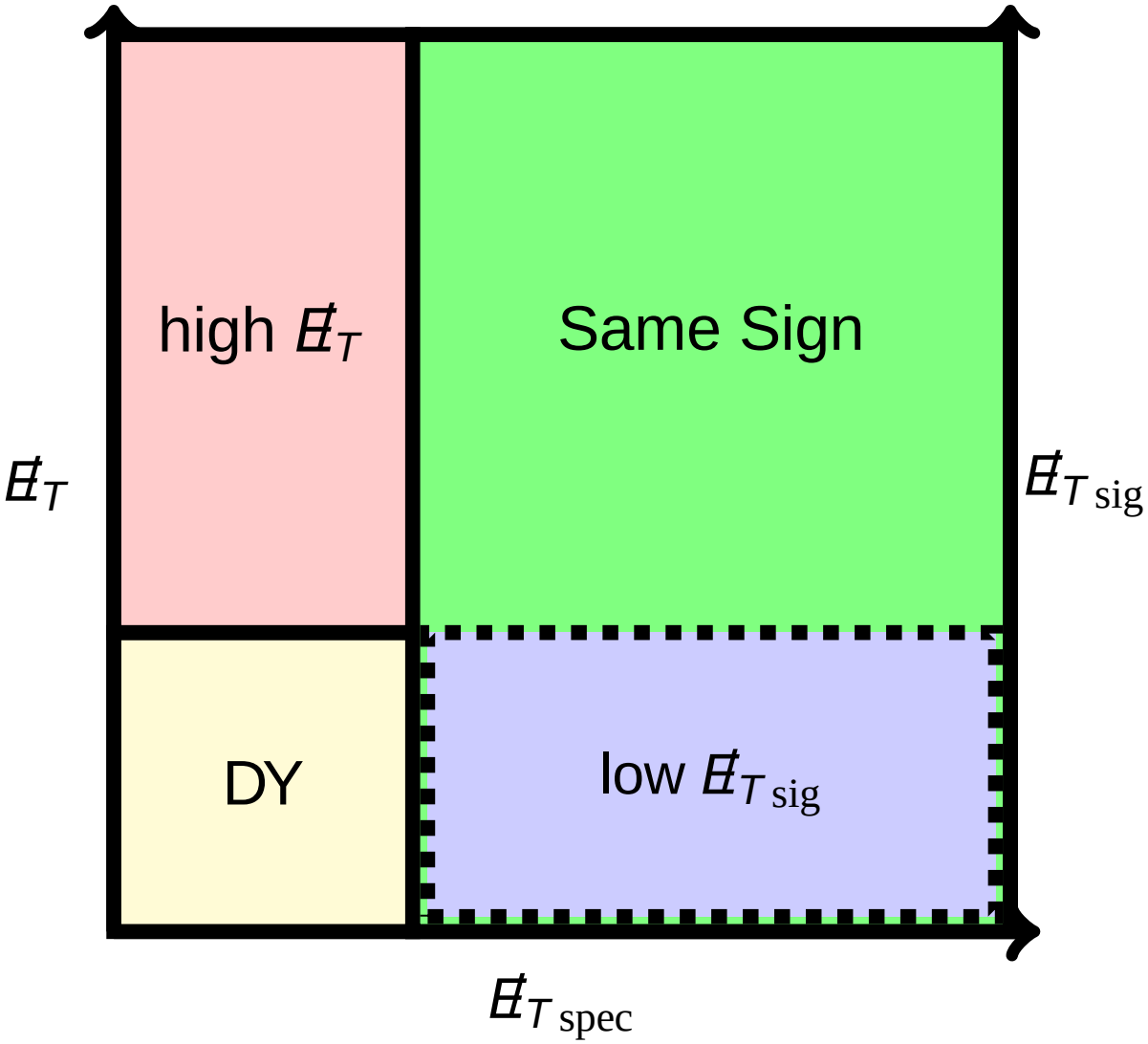
high $\not{E}_T$

test lepton mis-measurem

Same Sign

test conversion and fake

Cross check



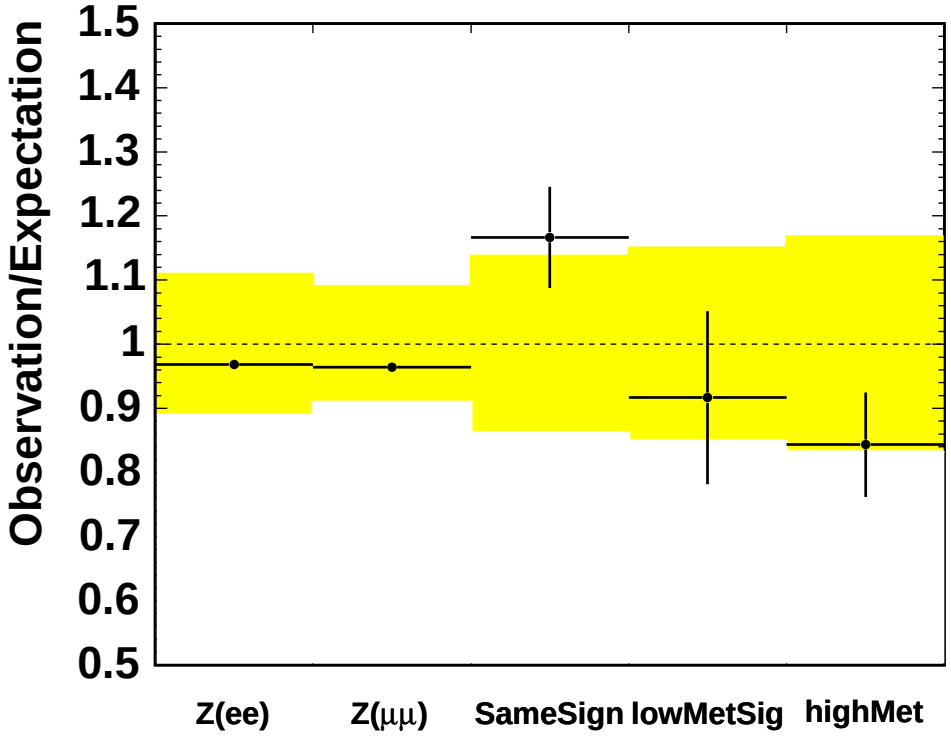
DY
test lepton ID and trigger

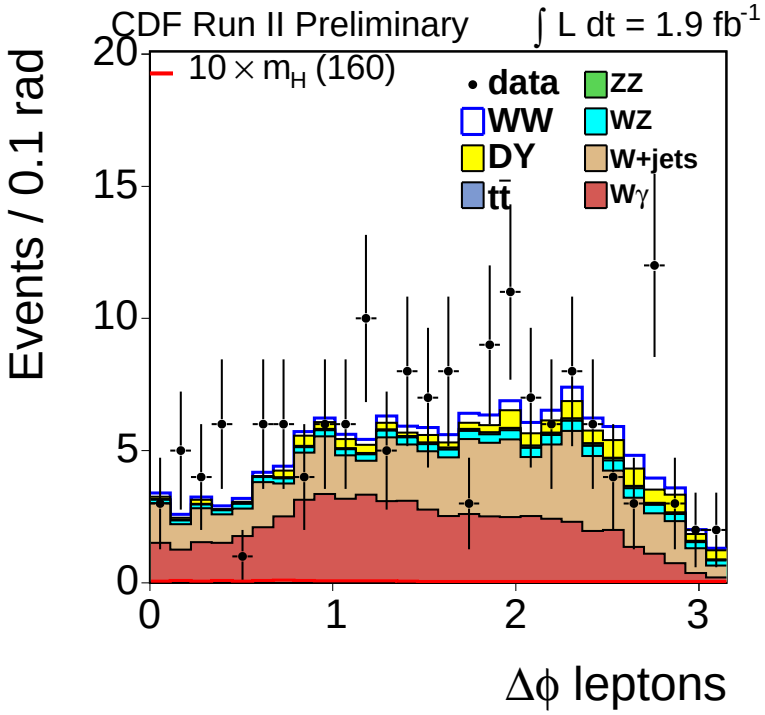
high $\not{E}_T$
test lepton mis-measurem

Same Sign
test conversion and fake

low $\not{E}_{T\,\mathrm{sig}} (= \not{E}_T / \sigma_{\not{E}_T})$
$\sigma_{\not{E}_T} = \sqrt{\sum E_T}$
test unclustered energy

Cross Check Results

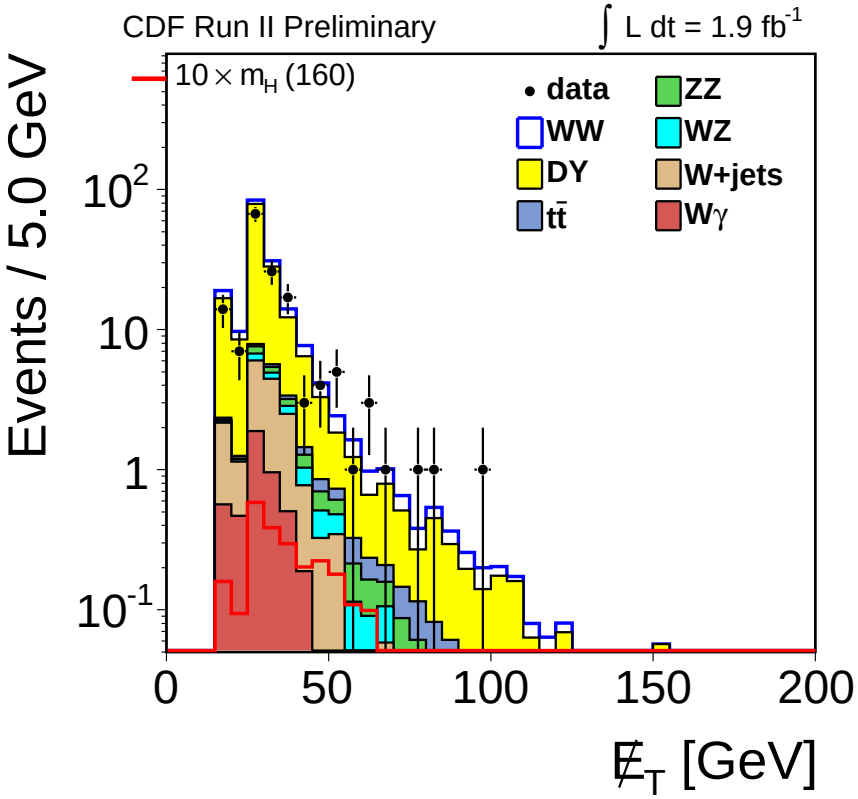


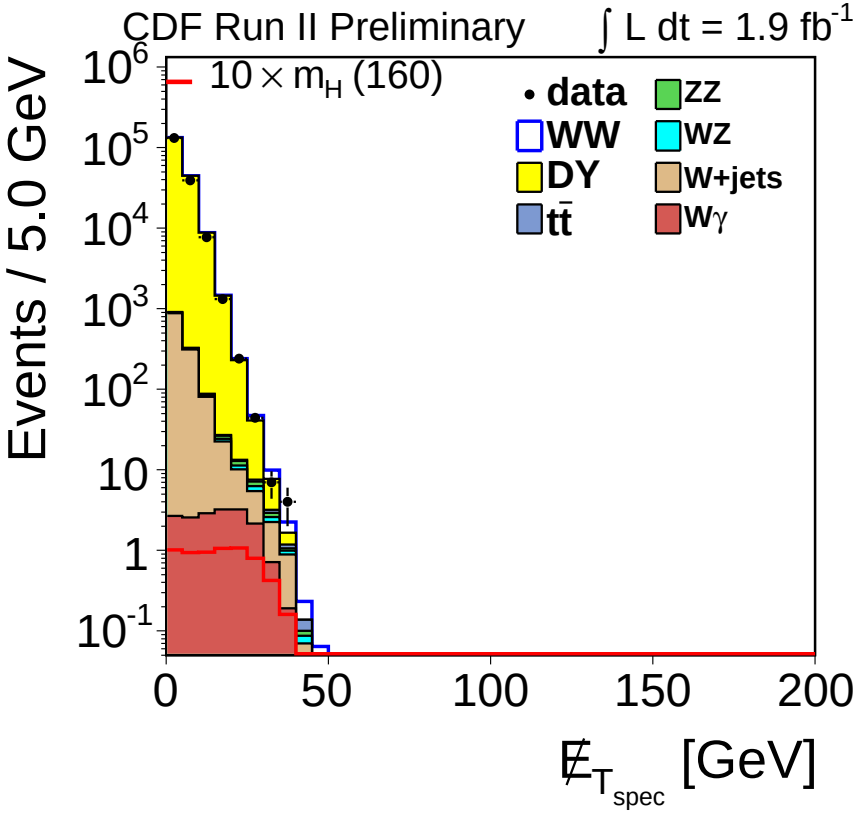


- Yellow band is systematics
- high $\not{E}_T$ region determines 20% $\not{E}_T$ systematics for DY

- Same Sign

Cross Check Results





- high $\not{E}_T$

  $\not{E}_{T\,\mathrm{spec}} < 25\ \mathrm{GeV}(15\ \mathrm{if}\ e\mu)$

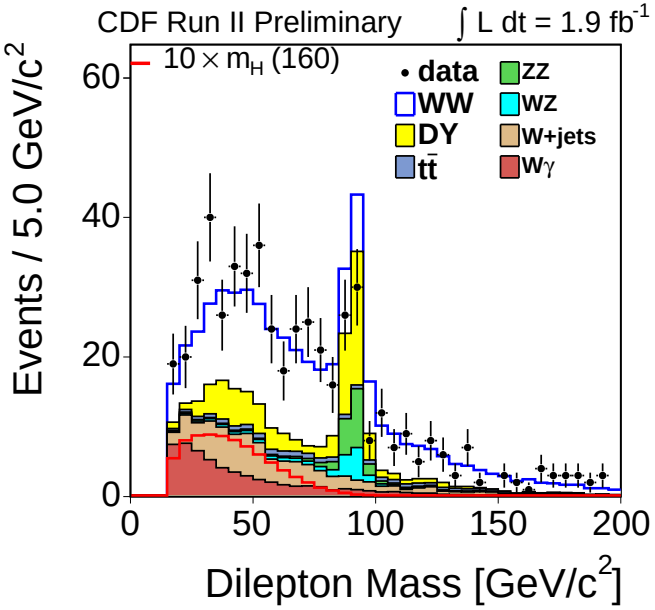
- low $\not{E}_{T\,\mathrm{sig}}$

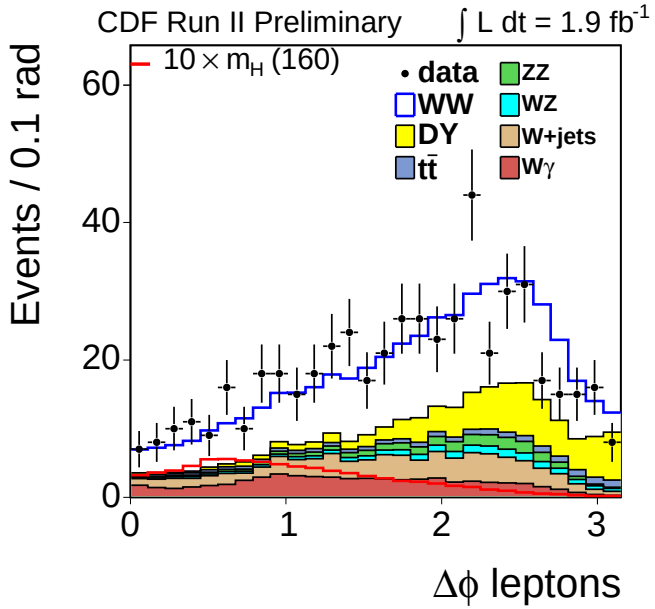
  $$\frac{\not{E}_T}{\sqrt{\sum E_T}} < 2.5$$

Candidate Events in Signal Region

CDF Preliminary with $1.9 fb^{-1}$

Contribution	Expected Events
WW	251 ± 36
Drell-Yan	82 ± 16
W+jets	67 ± 14
WZ	17 ± 3
ZZ	21 ± 3
$W\gamma$	59 ± 12
$t\bar{t}$	17 ± 3
Sum Bkg	513 ± 41
Data	522





- N($m_H = 160 GeV/c^2$)=7.8
- $W\gamma$ has similar kinematics to Higgs ($m_H < 160 Dev/c^2$)

Perform Multivariate Analysis - Matrix Element Method

- Discriminate signal from irreducible backgrounds

The Analysis Flow

Use all leptonic information

- 8 input: $\vec{P_{l^+}}, \vec{P_{l^-}}, \not{E}_{Tx}, \not{E}_{Ty}$

The Analysis Flow

Use all leptonic information

- 8 input: $\vec{P_{l^+}}, \vec{P_{l^-}}, \not{E}_{Tx}, \not{E}_{Ty}$

Calculate Event Probability

- 5 event probabilities output
- Prob: $H \rightarrow WW$, $p\bar{p} \rightarrow WW$, $p\bar{p} \rightarrow ZZ$, $p\bar{p} \rightarrow W\gamma$, $p\bar{p} \rightarrow W$+1jet

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Construct Likelihood Ratio Discriminator

- 1 output
- $LR = \frac{P_{Higgs}}{P_{Higgs} + \Sigma f_{b_j} P_{b_j}}$, where $\Sigma f_{b_j} = 1$ and f_{b_j} are fractions of expected yields

The Analysis Flow

Use all leptonic information

- 8 input: $\vec{P_{l^+}}, \vec{P_{l^-}}, \not{E}_{Tx}, \not{E}_{Ty}$

Calculate Event Probability

- 5 event probabilities output
- Prob: $H \rightarrow WW$, $p\bar{p} \rightarrow WW$, $p\bar{p} \rightarrow ZZ$, $p\bar{p} \rightarrow W\gamma$, $p\bar{p} \rightarrow W$+1jet

Construct Likelihood Ratio Discriminator

- 1 output
- $LR = \frac{P_{Higgs}}{P_{Higgs} + \Sigma f_{b_j} P_{b_j}}$, where $\Sigma f_{b_j} = 1$ and f_{b_j} are fractions of expected yields

Build LR templates of signal and all backgrounds!

Event Probability Calculation

Matrix Element Method

Leading order probability density using the full kinematic information

$$P(x_{obs}) = \frac{1}{<\sigma>} \int \frac{d\sigma_{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

x_{obs} : observed “leptons” and $\vec{\not{E}}_T$ y: true value

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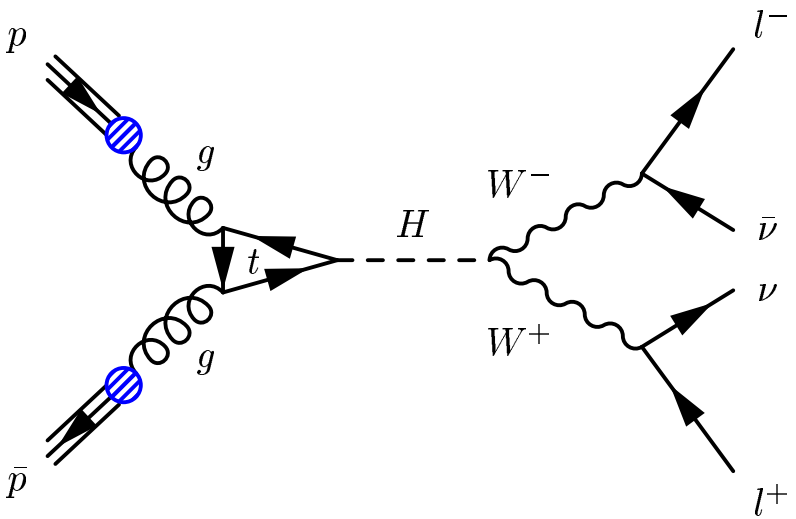
x_{obs} : observed "leptons" and $\vec{\not{E}}_T$ y: true value

$\frac{d\sigma_{th}}{dy}$ MCFM LO cross-section



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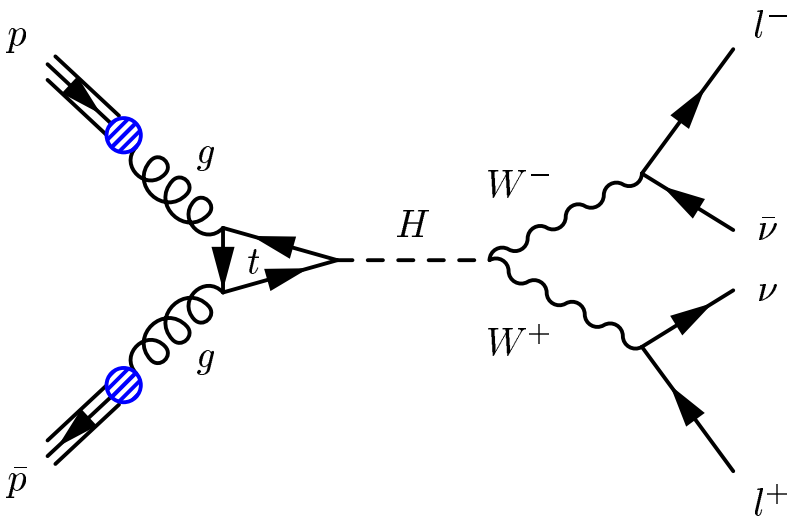
x_{obs} : observed "leptons" and $\vec{\not{E}}_T$

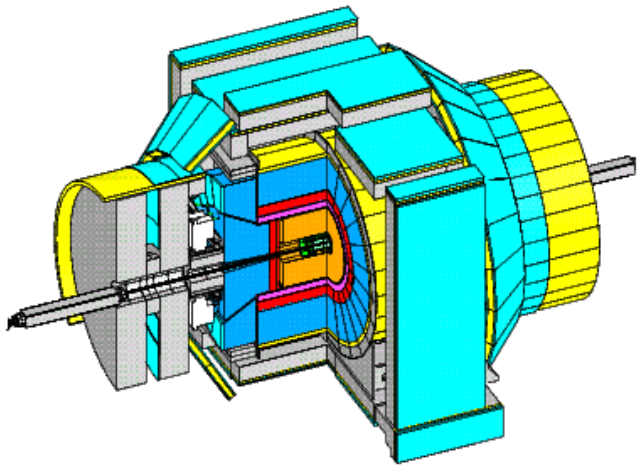
y: true value

$\epsilon(y)$ efficiency $\times$ acceptanc

$G(x_{obs}, y)$ resolution effects

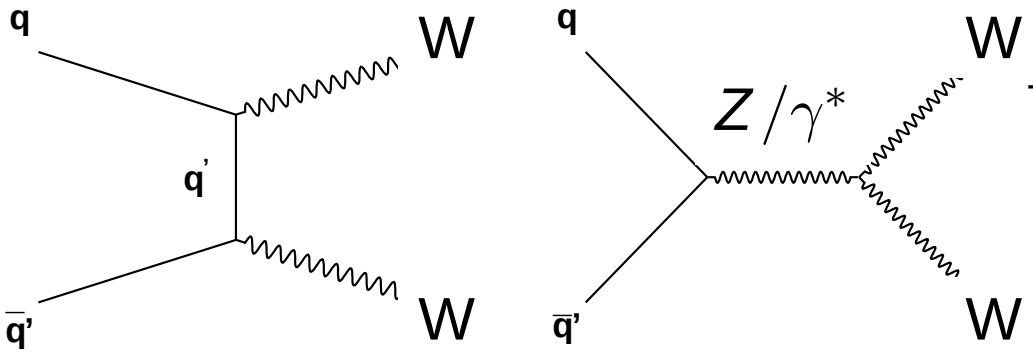
$\frac{d\sigma_{th}}{dy}$ MCFM LO cross-section

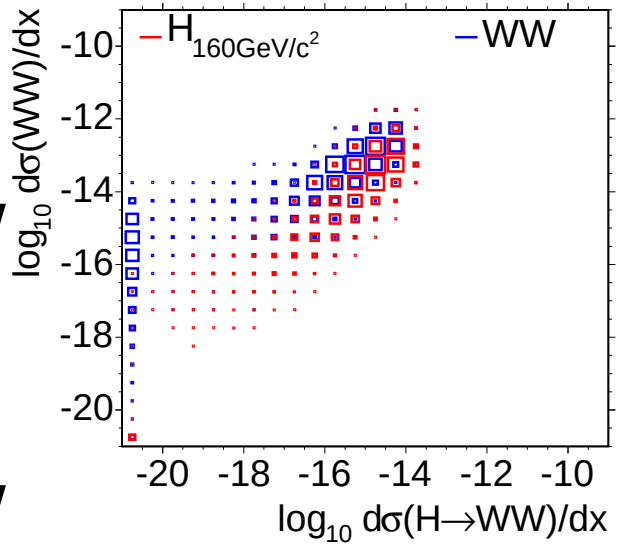




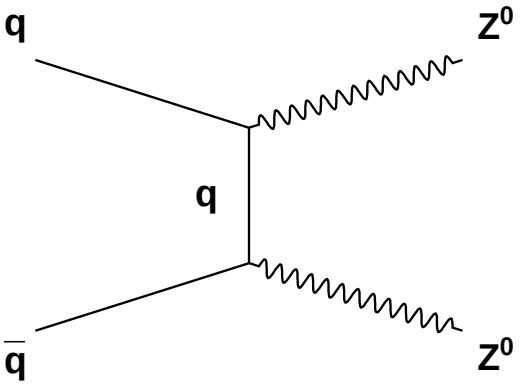
Calculate P_{WW} and P_{ZZ}

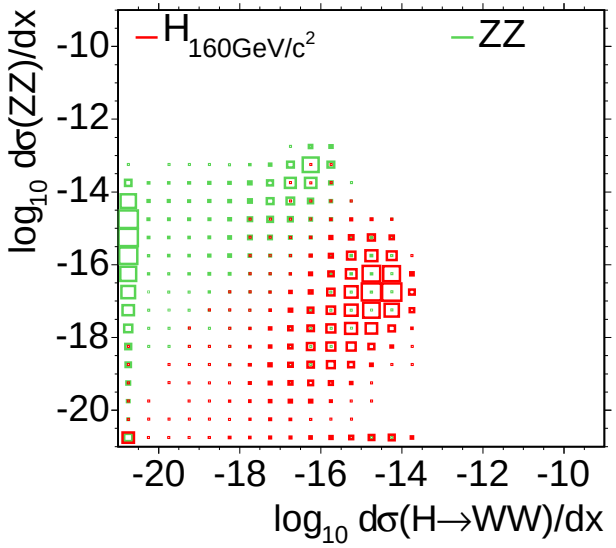
- P_{WW}: 8D Integration
  $M_{W^+}, M_{W^-}, \nu_z, \bar{\nu}_z, E_{l^+}, E_{l^-}, k_x, k_y$



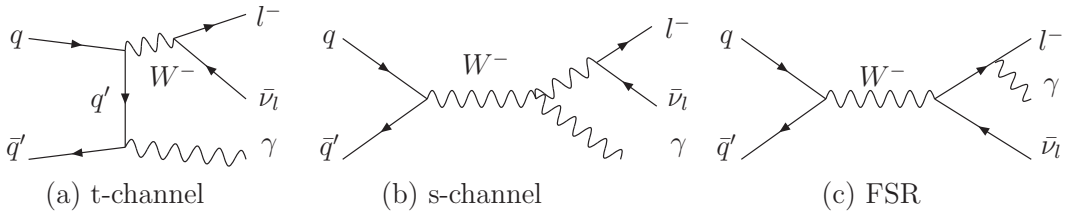


- P_{ZZ}: 8D Integration
  $M_Z, \nu_x, \nu_y, \nu_z, E_{l^+}, E_{l^-}, k_x, k_y$

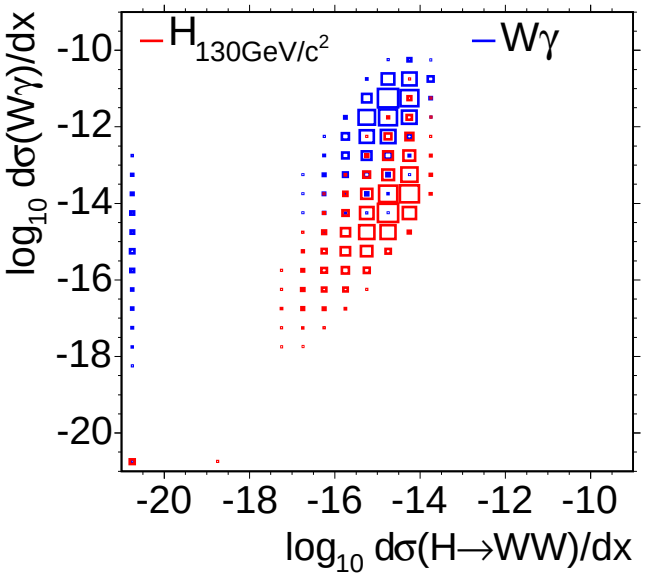


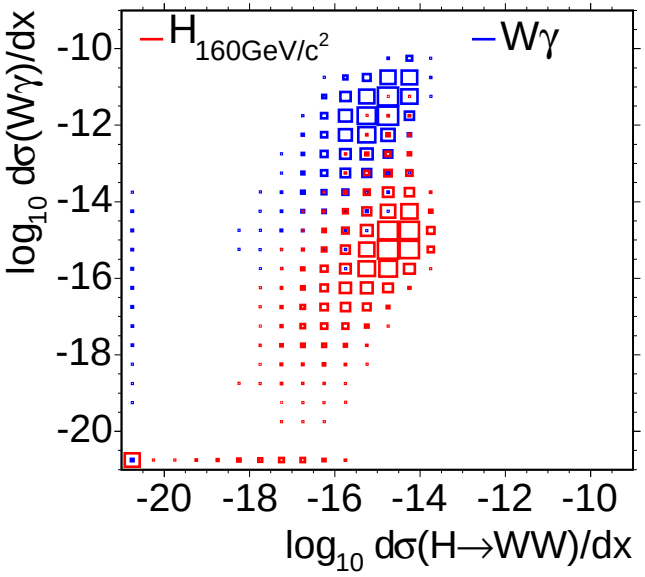


Calculate $P_{W\gamma}$



- 5D Integrations: $m_W, k_x, k_y, E_{T1}, E_{T2}$
- Construct $P_{\gamma \to lepton}$ from Monte Carlo
- $P_{W\gamma}$ could discriminate $W\gamma$ from Higgs
- Less discrimination power for $M_H < 160$ GeV/c^2



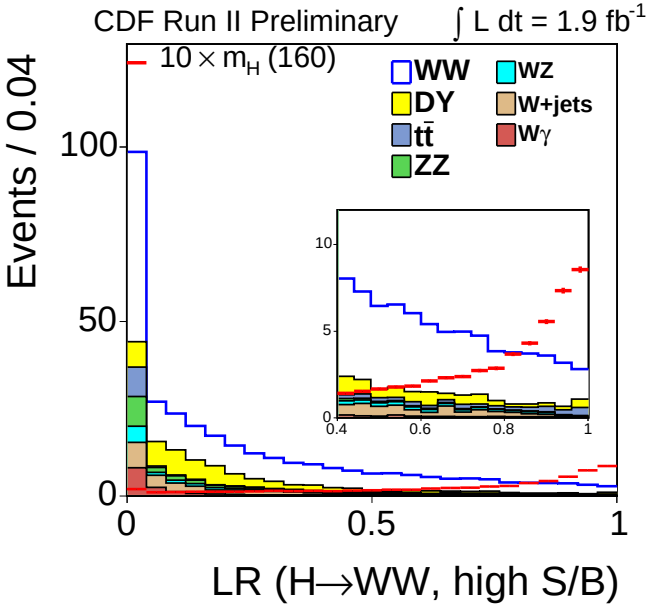


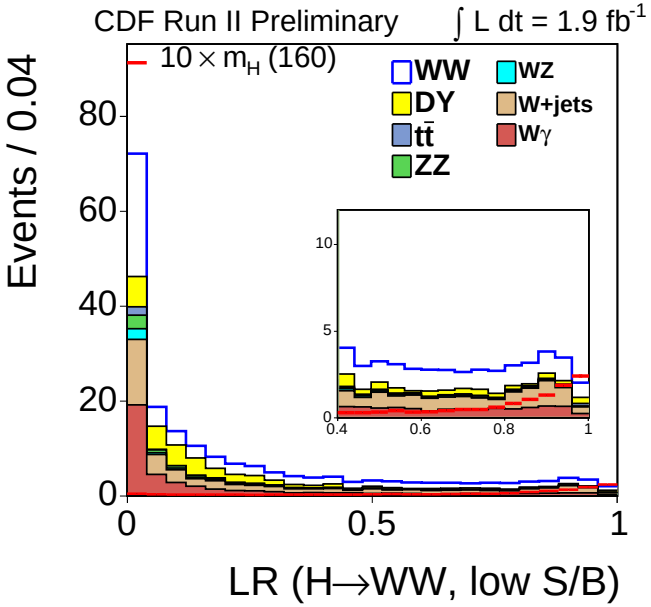
Evaluate Sensitivity

- Define Likelihood Ratio Discriminator

$$LR = \frac{P_{Higgs}}{P_{Higgs} + \Sigma_i f_{b_i} P_{b_i}}, \ \Sigma_{b_i} f_{b_i} = 1$$

- Two dilepton categories based on S/B ratio





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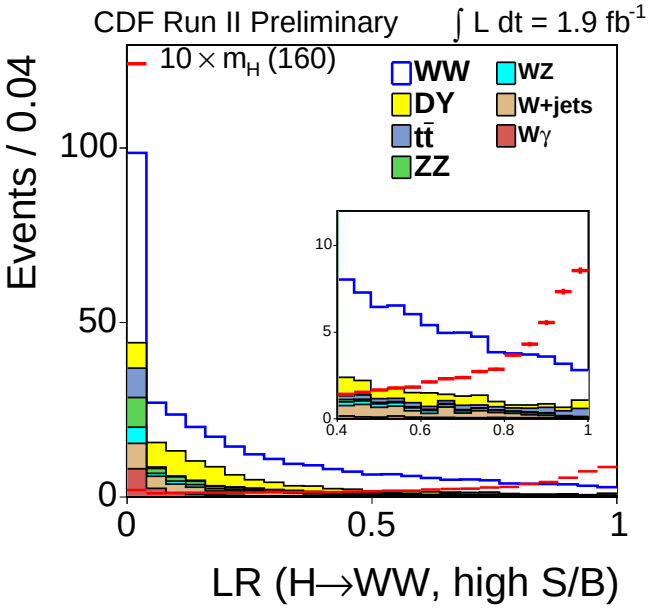
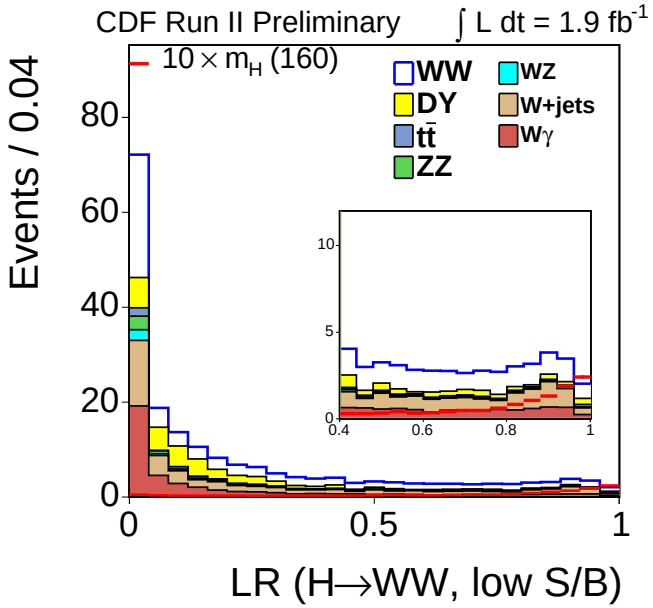




- Bayesian Fitting to set 95% Confidence Level limit

$$L(s, b_j) = \Pi \frac{e^{-\mu_i} \mu_i^{n_i}}{n_i!} G(b_{ij}, \sigma_{ij}), \ \mu_i = s_i + \Sigma_j b_{ij}$$

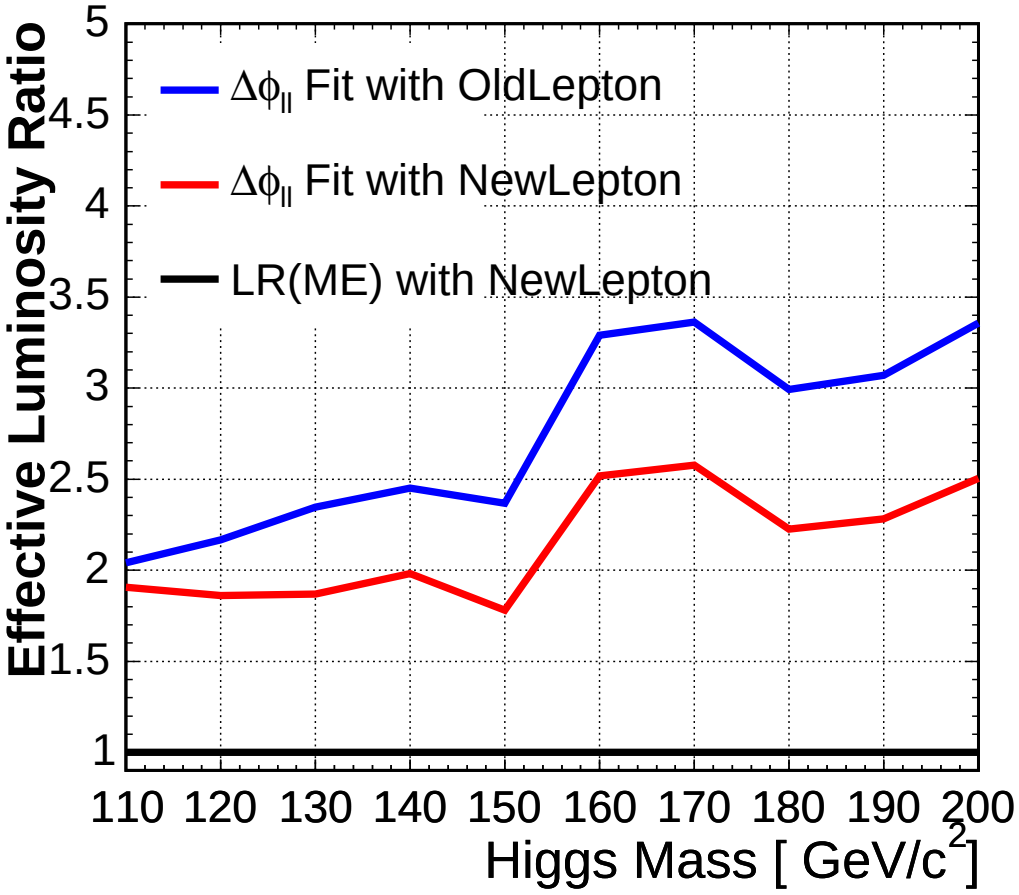
Systematics

- Systematics of 95% C.L. limit due to different sources
- Implemented correlations between backgrounds

Source	$\Delta\sigma_{95\%C.L.}(\%)$
Theoretical Xsec	8
NLO Acceptance	6
$\not{E}_T$ modeling	4
$W\gamma$ Conversion	2
W+jets fake	3
trigger efficiency	3
PDF	2
lepton ID	1
luminosity	5
Total	13

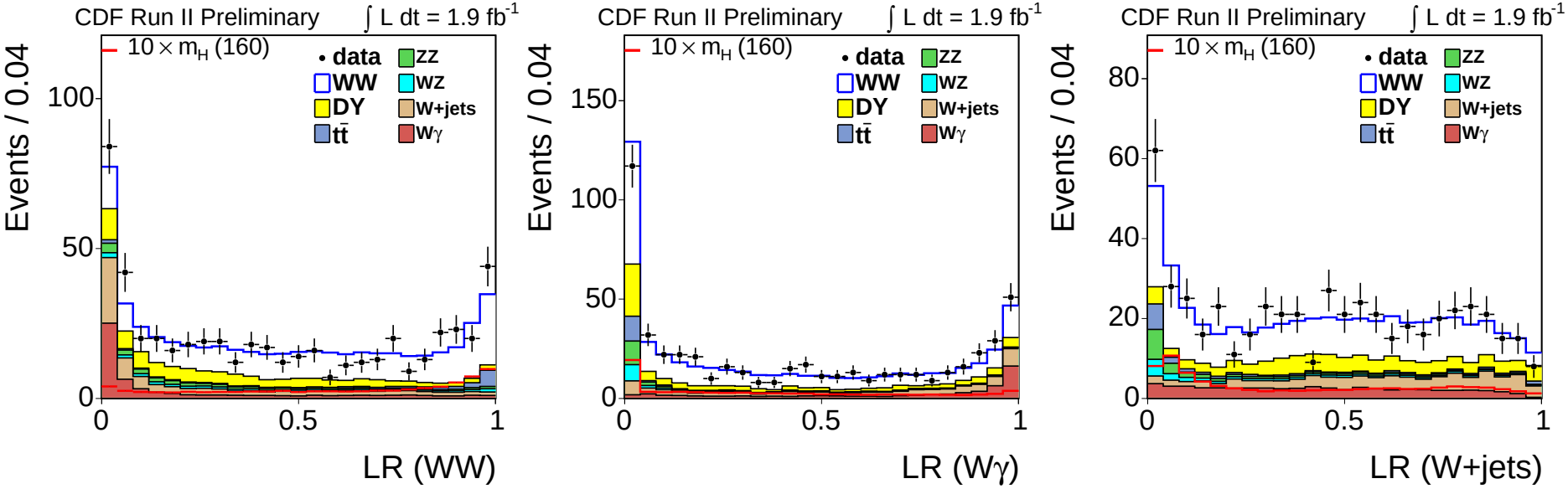
Improved Sensitivity

- Re-implement previous analysis PRL97, 081802 (2006)
- Factor of 1.2∼1.4 effective luminosity by adding new leptons
- Factor of 1.8∼2.6 effective luminosity by using new methods



Likelihood Ratio Cross Check

- Alternative definition of likelihood ratio to treat background event probability as signal
- P_{Higgs} isn't included

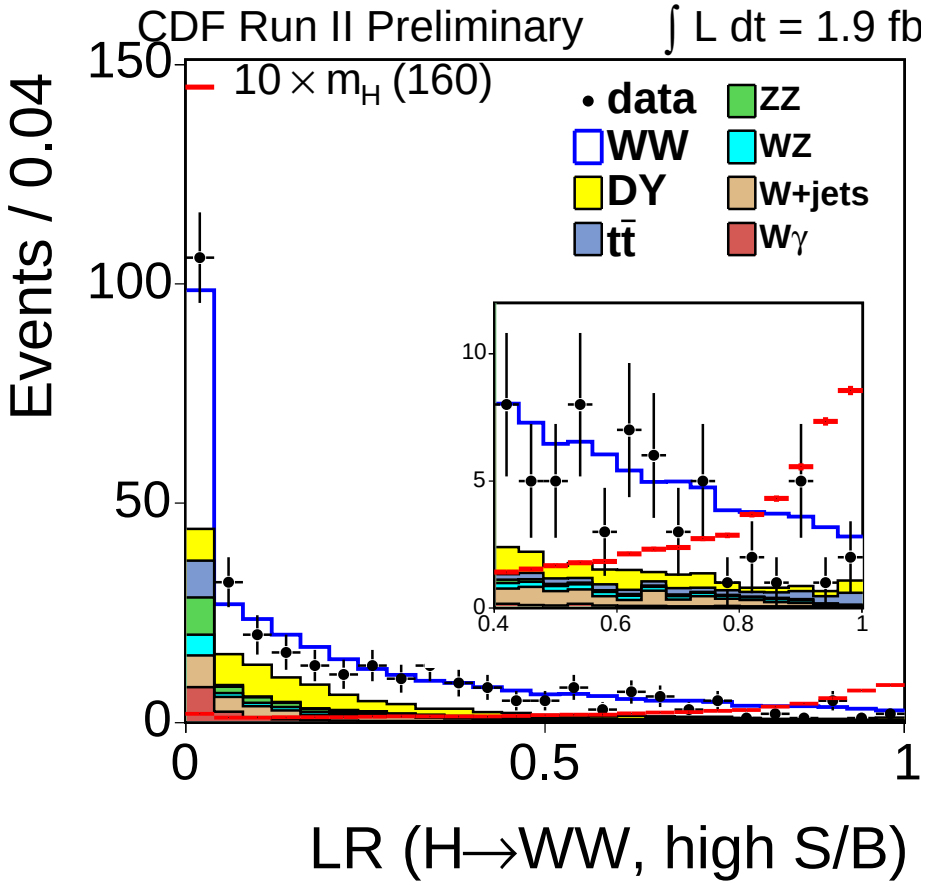


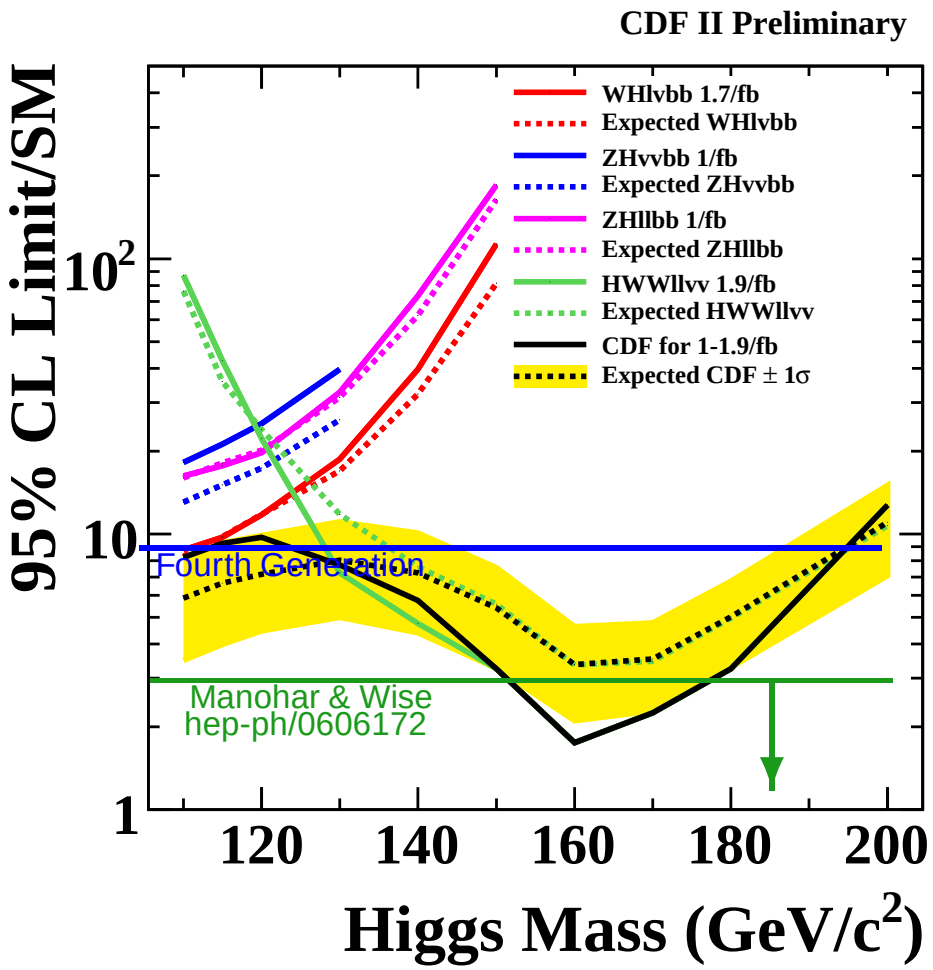
$$\frac{P_{WW}}{P_{WW}+\Sigma P_{b_j}} \qquad \frac{P_{W\gamma}}{P_{W\gamma}+\Sigma P_{b_j}} \qquad \frac{P_{W+jets}}{P_{W+jets}+\Sigma P_{b_j}}$$

Results

$H \rightarrow WW^*$ Search Results

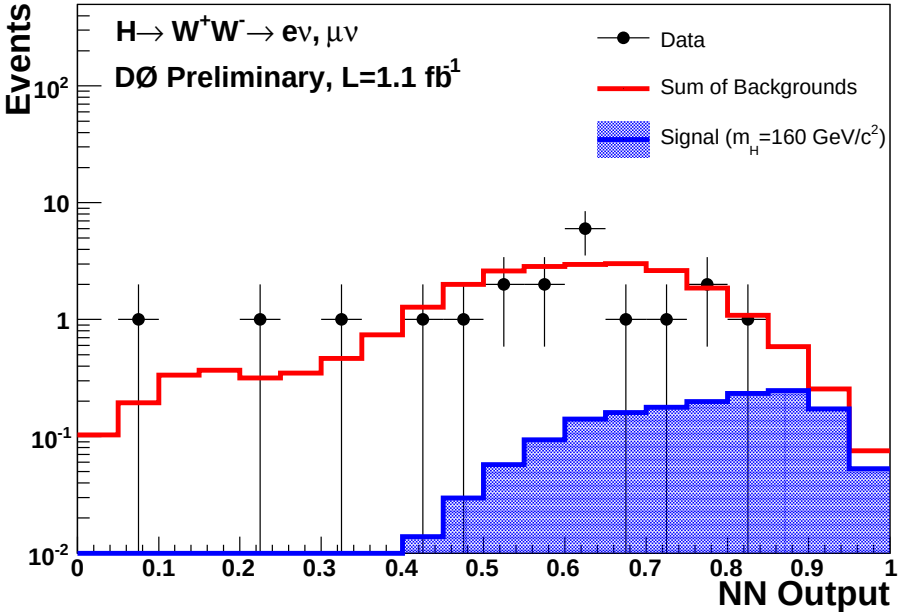
- Dominant limits for $m_H > 135$ GeV/c^2
- Factor of 2 from SM at $m_H > 160$ GeV/c^2

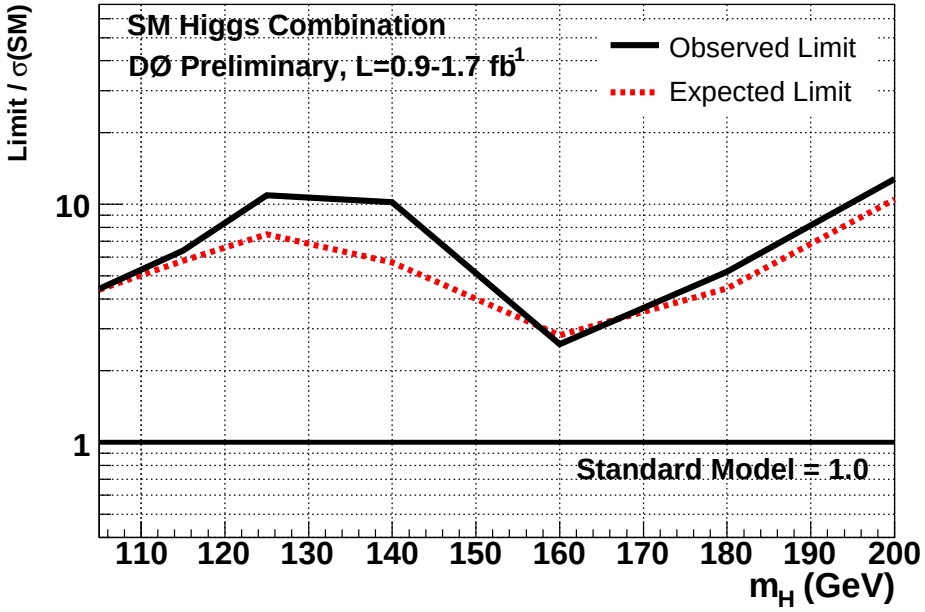




Comparison to D0

- Similar expected sensitivity while CDF has downward fluctuation at $m_H = 160$ GV/c^2
- Monte Carlo based estimation for W+jets/γ
- Tighter event selection: N_s/N_b=5/69.
- Neural Net Discriminator: 5 or 6 input variables

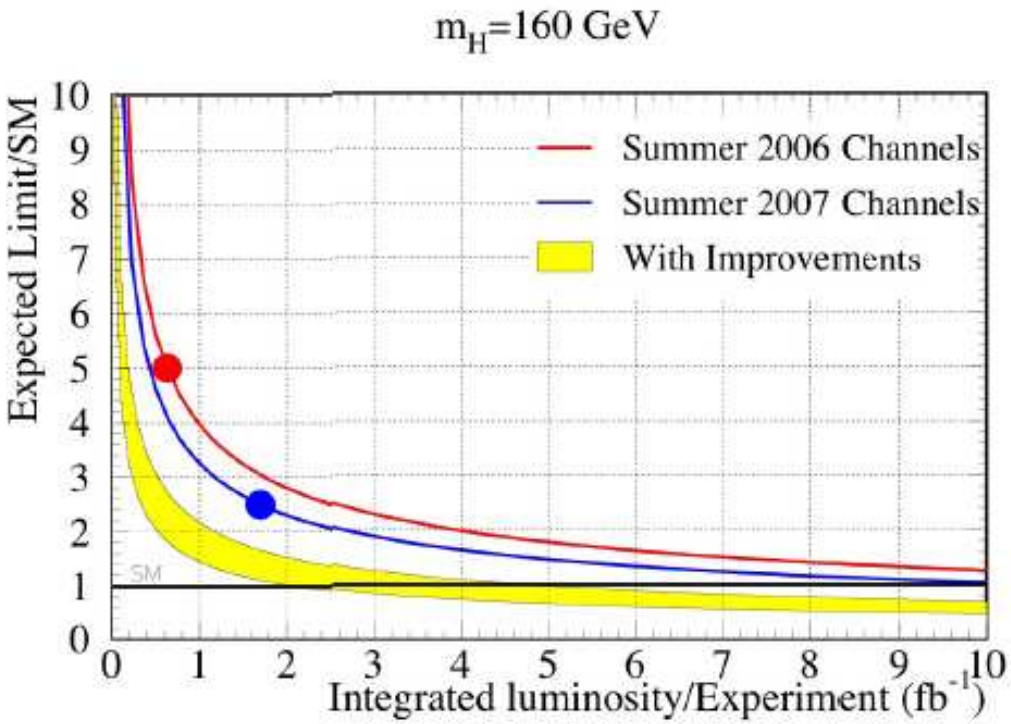




Prospects at CDF/Tevatron

Factor of 2 improvement:

- NN+ME 10%
- VBF inclusion10%
- Hadronic tau 10%
- 2 jet bin 10%
- D0 combination $\sqrt{2}$

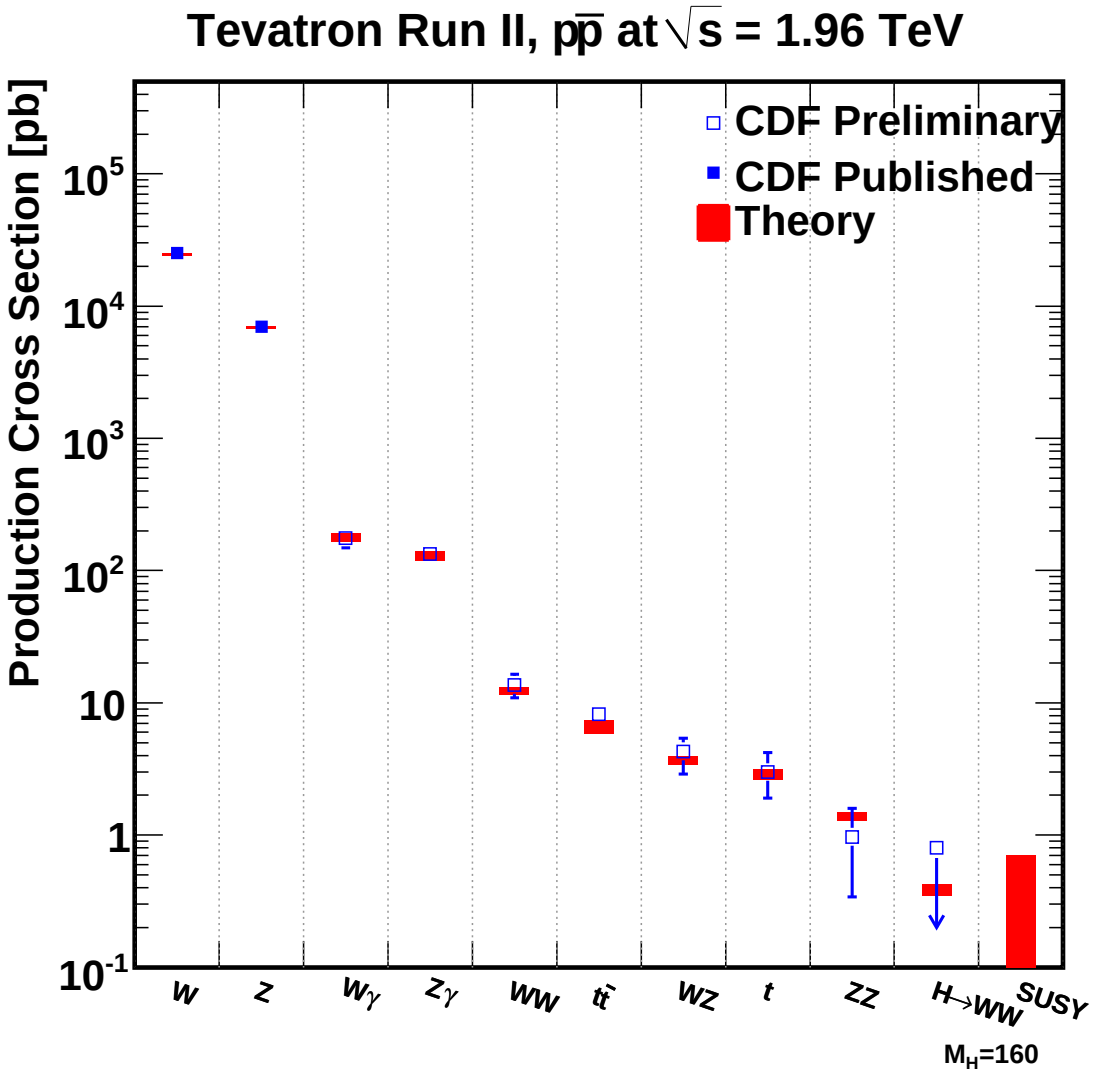


- Yellow band reprensents the range of expected limits after improvements (presented in P5)
- Will soon be excluding (if it's not there!) Higgs bosons around 160 GeV/c^2

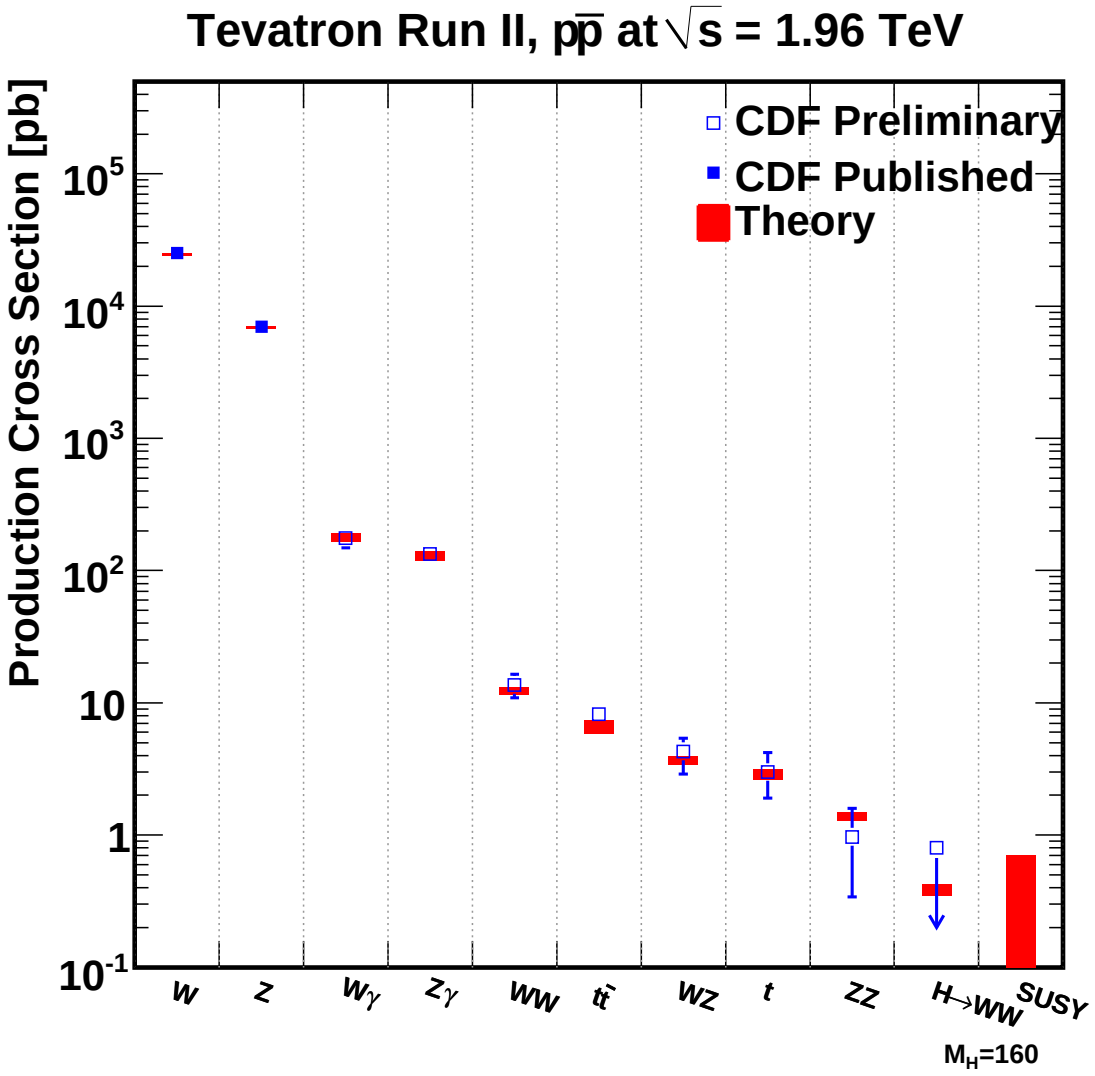
Summary

- Improvements of Higgs search sensitivity: $2.2 \sim 3.4 \times \mathcal{L}_{eff}$
  - Additional Leptons: $1.2 \sim 1.4 \times \mathcal{L}_{eff}$
  - Matrix Element Method: $1.8 \sim 2.6 \times \mathcal{L}_{eff}$
- These packages are widely used in Diboson and $H \rightarrow WW$ group
- The analysis results have me as one of the primary authors:
  - WZ (published in PRL98 161801(2007))
  - $H \rightarrow WW^*$ (public result, paper being written)
  - ZZ (new results will be released soon)
  - WW cross-section (result being updated before publication)

Current Experimental Status



Current Experimental Status



Higgs is the next!

Backup Slides

Estimate W+jets

Data Derived Estimate of W+jets Background

- Measure rate jets are midentified as leptons in multi-jet QCD data
  - Assumes jets in multijet events are the same as in W+jets

1. Calculate in the jet data

$$\text{Fake Rate} = \frac{\#\text{Identified Leptons}}{\#\text{Denominator Objects}}$$

2. Correct for W and Z contamination using Monte Carlo
3. Scale data W+"denominator object" events by measured fake rate

Systematics Breakdown

	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Higgs
$\not\!\!E_T$ Modeling	1.0	1.0	1.0	1.0	20.0	1.0	-	1.0
Conversions	-	-	-	-	-	20.0	-	-
NLO Acceptance	5.5	10.0	10.0	10.0	5.0	10.0	-	10.0
Cross-section	10.0	10.0	10.0	15.0	5.0	10.0	-	-
PDF Uncertainty	1.9	2.7	2.7	2.1	4.1	2.2	-	2.2
LepId $\pm 1\sigma$	1.5	1.4	1.3	1.5	1.5	1.2	-	1.5
Trigger Eff	2.1	2.1	2.1	2.0	3.4	7.0	-	3.3
Total	11.9	14.7	14.6	18.4	21.9	25.6	22.5	10.9

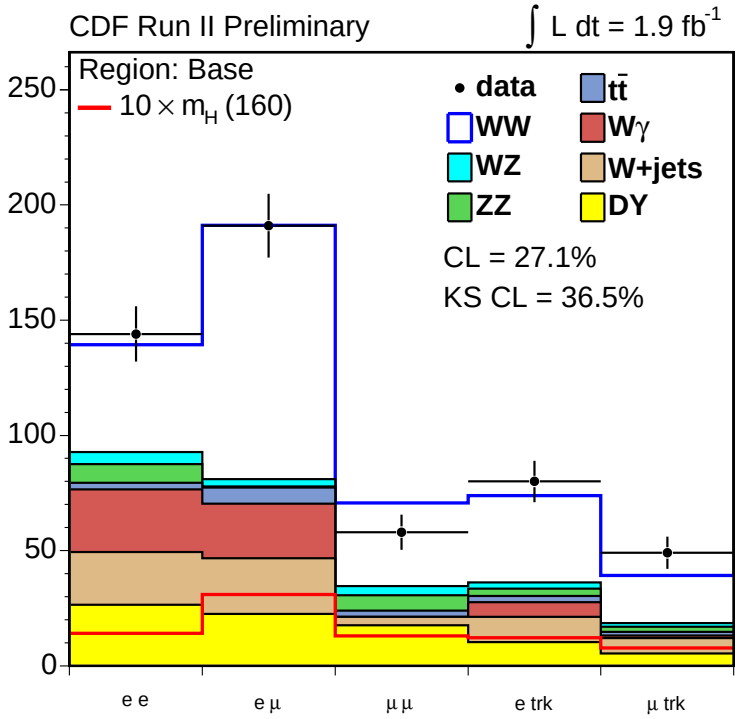
Fitted Results

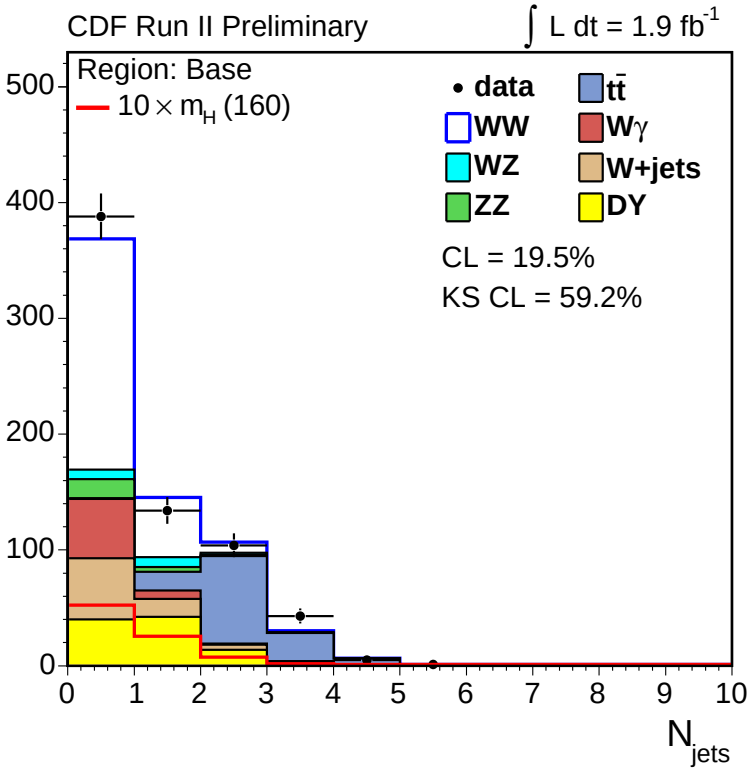
$M_H(GeV/c^2)$	110	120	130	140	150	160	170	180	190	200
$\sigma_{SM}(HWW)(pb)$	0.057	0.134	0.230	0.312	0.358	0.388	0.344	0.278	0.194	0.155
$median(pb)$	3.9	2.9	2.4	2.2	1.8	1.2	1.1	1.3	1.4	1.5
$Observed(pb)$	4.8	2.8	1.6	1.5	1.1	0.8	0.8	0.8	1.4	1.9
$+2\sigma/\sigma_{SM}$	139.4	45.1	21.0	13.7	10.4	6.1	6.5	9.1	13.7	19.5
$+1\sigma/\sigma_{SM}$	96.4	31.7	15.2	9.6	7.3	4.4	4.5	6.5	10.2	14.1
$median/\sigma_{SM}$	69.0	21.7	10.7	6.9	5.2	3.1	3.2	4.6	7.1	9.7
$-1\sigma/sigma_{SM}$	48.9	15.4	7.7	5.0	3.7	2.2	2.3	3.2	5.0	6.9
$-2\sigma/\sigma_{SM}$	35.9	11.2	5.8	3.8	2.9	1.6	1.7	2.4	3.8	5.2
$Observed/\sigma_{SM}$	83.0	20.9	7.0	4.7	3.2	2.0	2.4	3.0	7.0	11.6

Table 1: Expected and Observed Limit for Higgs at 1.9 fb^{-1} with Systematics (the ratios include the uncertainty on σ_{SM}).

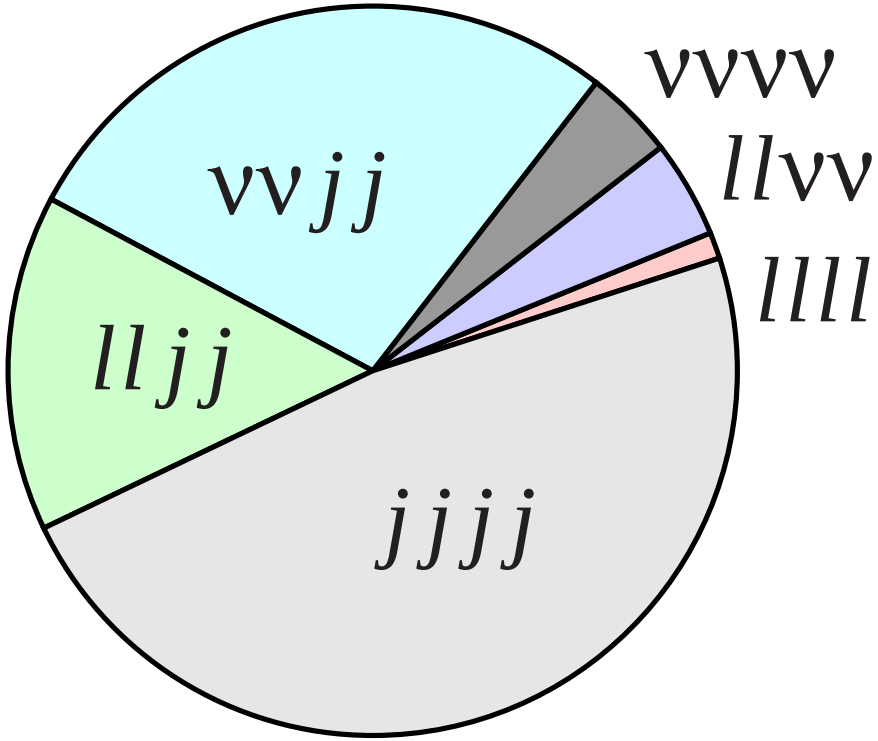
	Higgs Mass (GeV)									
Category	110	120	130	140	150	160	170	180	190	200
$e\ e$	0.1	0.3	0.6	0.9	1.2	1.4	1.4	1.1	0.8	0.6
$e\ \mu$	0.2	0.6	1.3	2.0	2.6	3.1	3.0	2.5	1.8	1.4
$\mu\ \mu$	0.1	0.2	0.5	0.8	1.1	1.3	1.3	1.0	0.7	0.6
e trk	0.0	0.2	0.4	0.7	0.9	1.2	1.2	1.0	0.7	0.6
μ trk	0.0	0.1	0.2	0.4	0.6	0.8	0.7	0.6	0.4	0.3
Total	0.4	1.3	3.0	4.8	6.4	7.8	7.6	6.2	4.4	3.5

More kinematics





Change Gears to ZZ Search



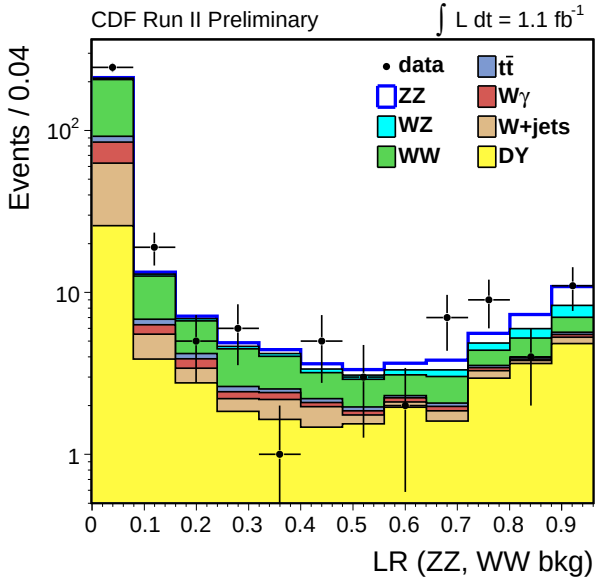
- $ZZ \rightarrow ll\nu\nu$ ($1.1 fb^{-1}$)
  - $N_S = 10.7$, $N_B = 142.2$, Observe 182 (1.9σ)
  - Use Matrix Elements to discriminate signal and background
- $ZZ \rightarrow$ 4 leptons ($1.3 fb^{-1}$)
  - $N_S = 2.55$, $N_B = 0.03$, Observe 1 (2.2σ)

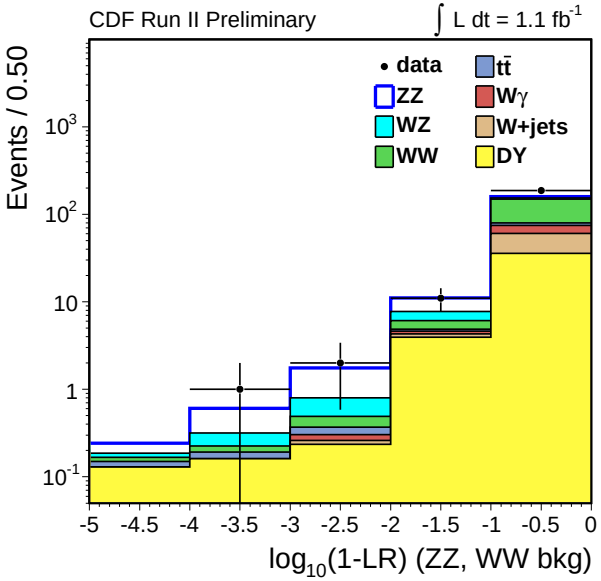
- Not observed in hadron collier yet $\sigma_{NLO}(p\overline{p} \rightarrow ZZ) = 1.4\ pb$
- Only using e or μ leptons

$$\sigma(ZZ) = 0.75^{+0.71}_{-0.54}(\text{stat.+sys.})\text{pb}$$

Significance of ZZ Production at 1.1$fb^{-}1$

Two Channels are Better than one

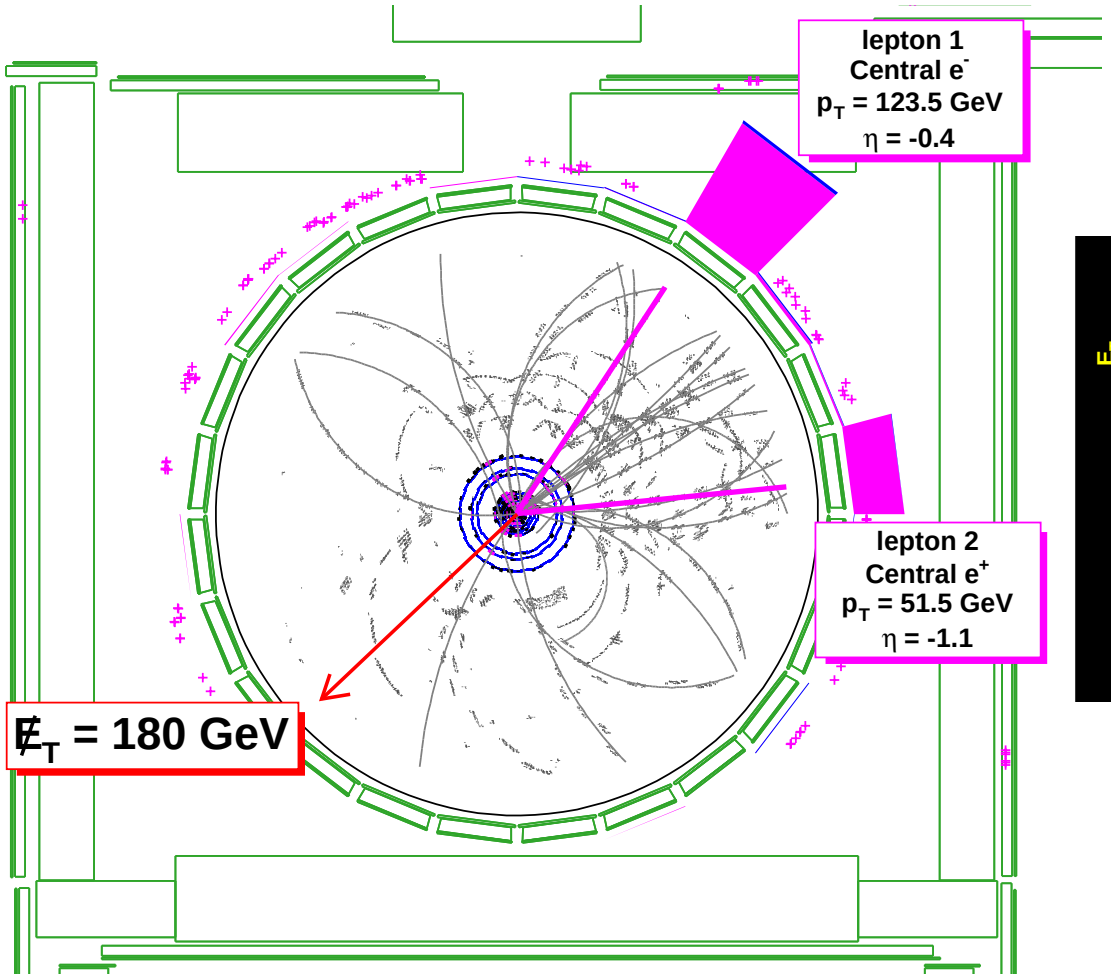


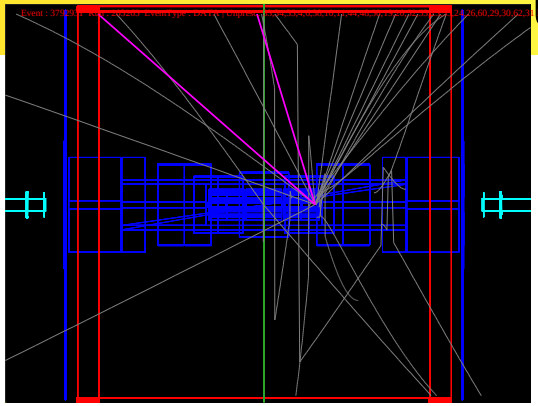


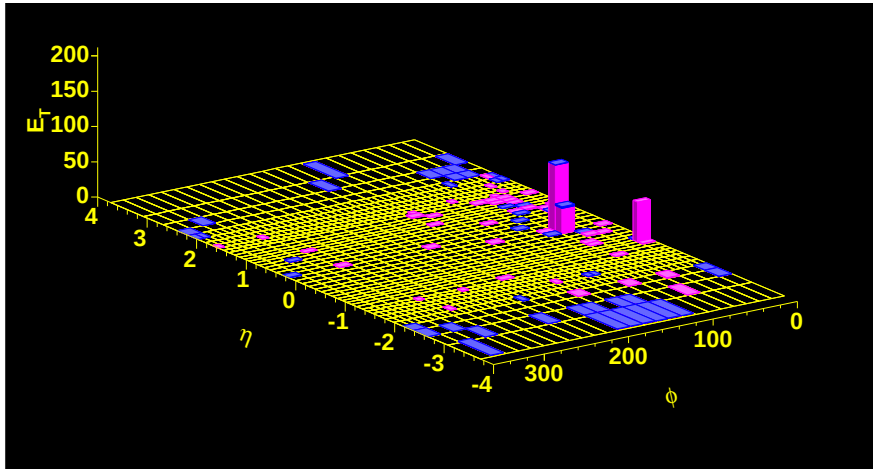
	$ll\nu\nu$	4 lepton	Combined
prob 2σ	0.50	0.92	0.88
prob 3σ	0.27	0.71	0.77
prob 5σ	0.05	0.24	0.51
Observed Significance	1.9 σ	2.2 σ	3.0 σ

New results at 1.9fb^{-1} will be released soon.

Most likely $ZZ \rightarrow ll\nu\nu$ event







Run=203265 Event=3792931

m_{12}=91.22 GeV

$|\not{E}_T|$=180.5 GeV

Type	p_T	η	ϕ
Central e	123.5	-0.4	1.0
Central e	51.5	-1.1	0.1