CDF実験での
$H \to WW \to l\nu jj$探索

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2012年7月6日(金)

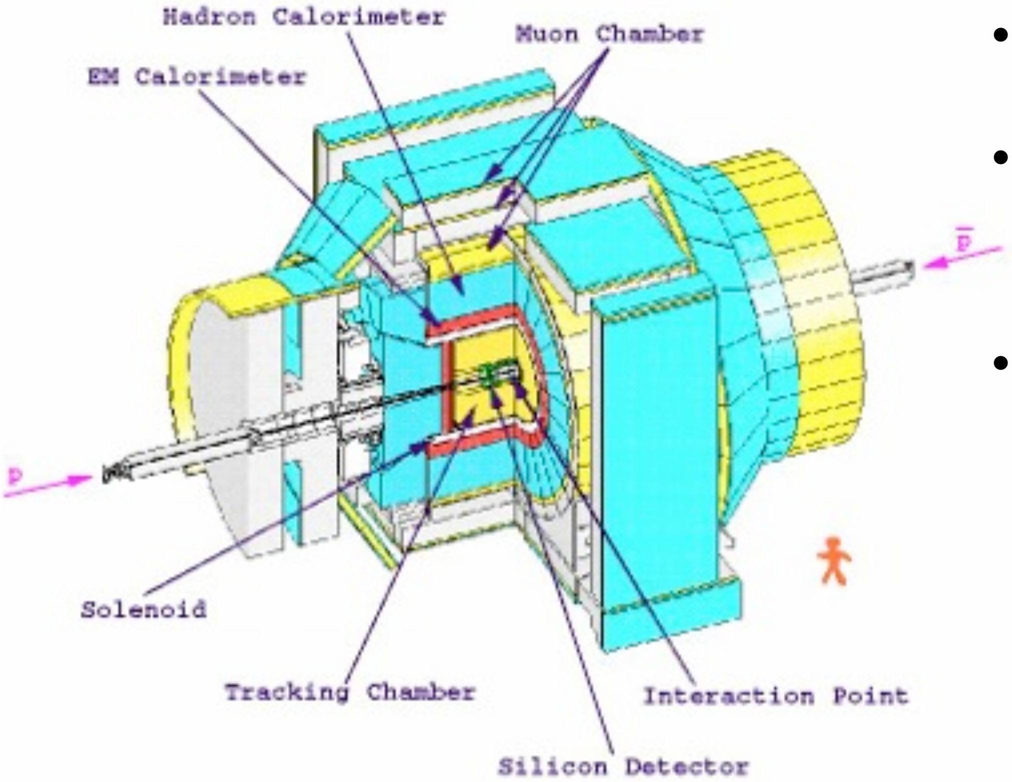
特定領域「フレーバー物理の新展開」研究会 2012

Tevatron Run II

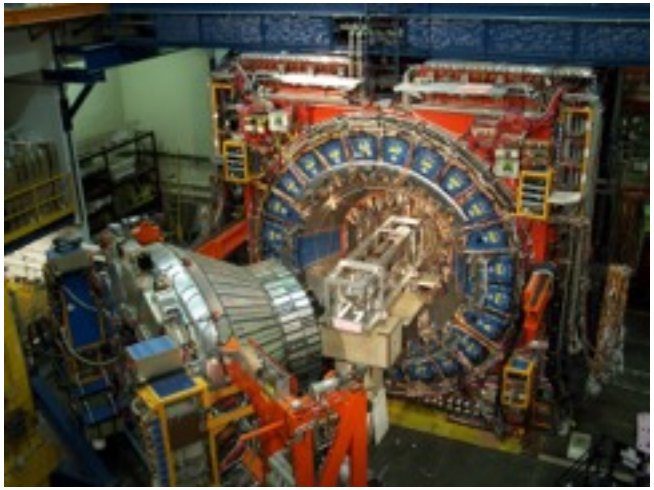
- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV (1.8 TeV in Run I).
- Run II:
  Summer 2001 - Autumn 2011.
- Collisions at world highest energy until Nov 2009.
  - Energy frontier for ～25 years!!
- Two multi-purpose detectors (CDF and D0) for wide range of physics studies.
- Delivered: 12 fb^{-1}.
  - Recorded by CDF: 10 fb^{-1}.
  - Recorded by D0: 10 fb^{-1}.

Collider Detector at Fermilab

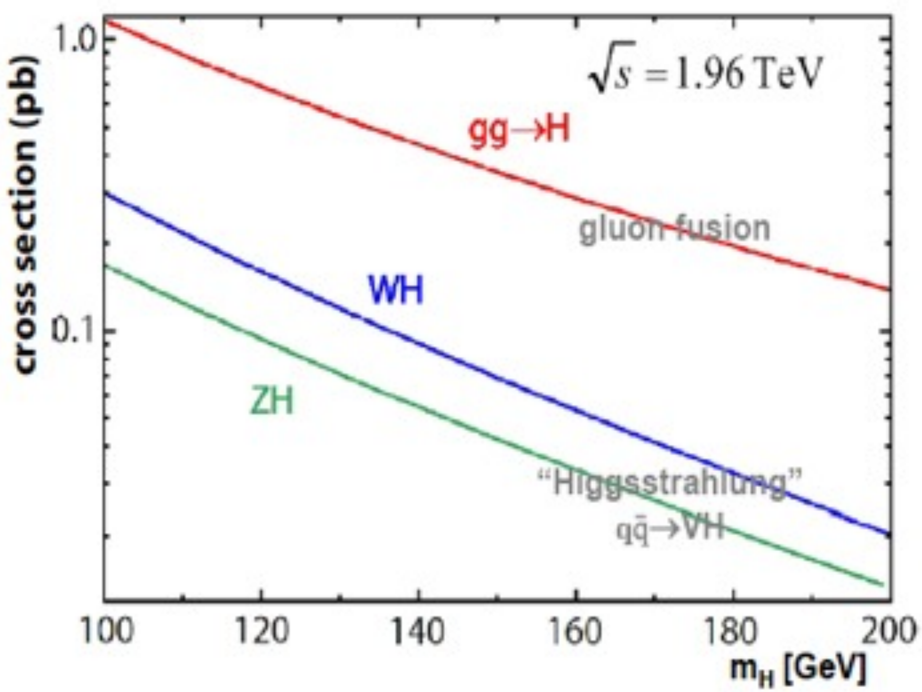
Multi-purpose detector

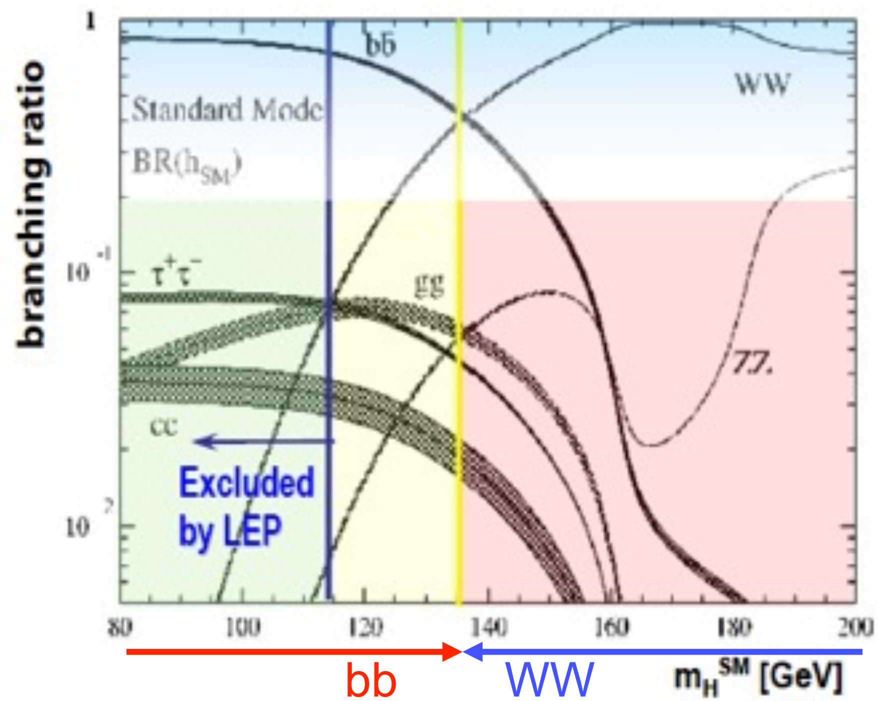


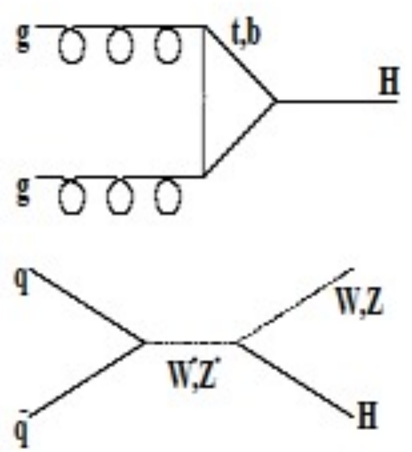
- Tracking in 1.4 T magnetic field.
  - Coverage $|\eta|<\sim 1$.
- Precision tracking with silicon.
  - 7 layers of silicon detectors.
- EM and Hadron Calorimeters.
  - $\sigma_E/E \sim 14\%/\sqrt{E}$ (EM).
  - $\sigma_E/E \sim 84\%/\sqrt{E}$ (HAD).
- Muon chambers.



SM Higgs Properties at Tevatron



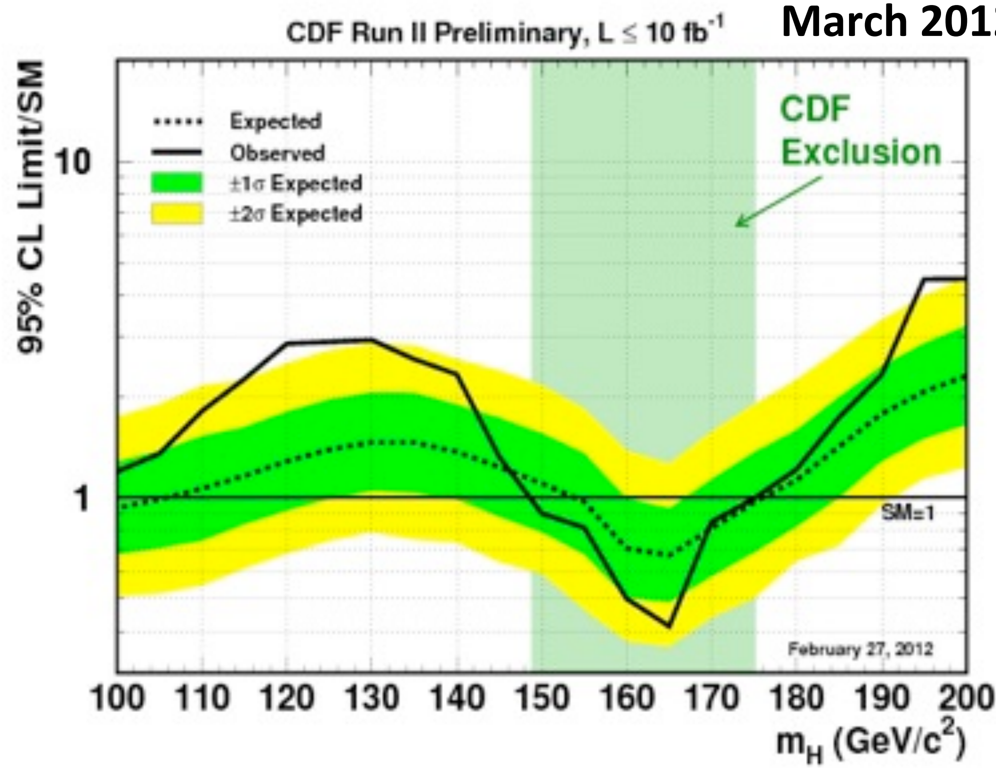


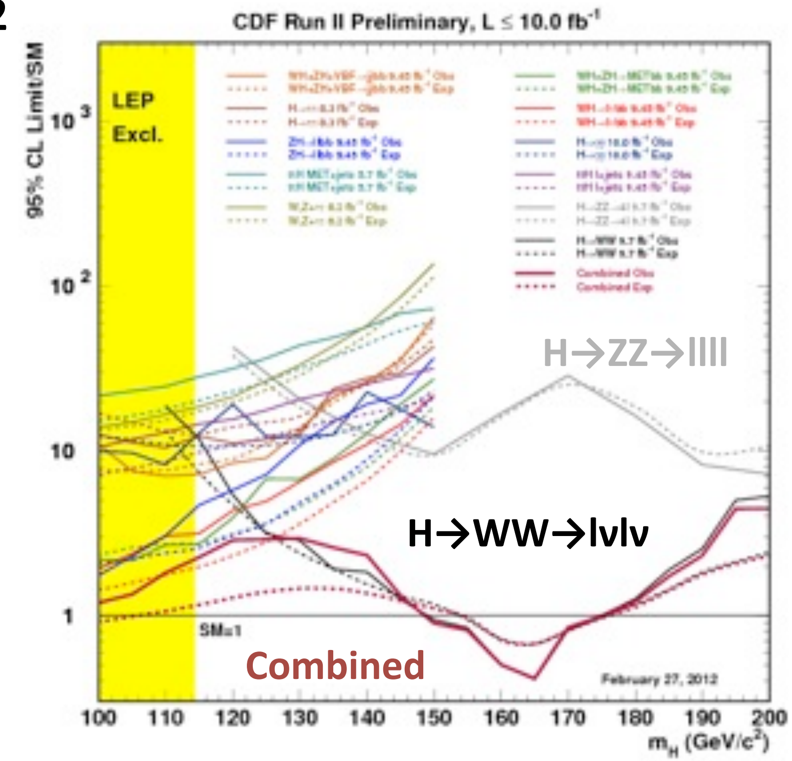


- Production cross section: *O(0.1)* fb.
- m_H<135 GeV/c^2 (low mass):
  - Look for WH/ZH with leptonic vector boson decays.
- m_H>135 GeV/c^2 (high mass):
  - Easiest to look for H→WW with one or two W decaying to lepton.

Status of CDF Higgs Search

March 2012





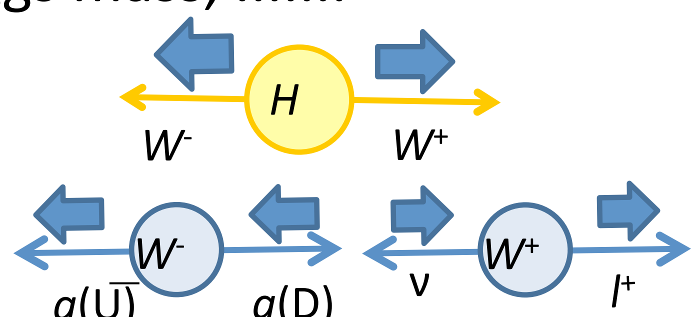
- At CDF in the high Higgs mass region (m_H>135 GeV/c^2):
  - We had a state of art analysis on $H \rightarrow WW \rightarrow l\nu l\nu$ channel.
  - Search in the high Higgs mass region were dominated by this single analysis.
  - **Not many other channels had been explored.**

Motivation and Analysis Idea

$H \rightarrow WW \rightarrow l\nu jj$

- H→WW is a promising decay mode for SM Higgs search for $m_H \geq 135$ GeV.
- The branching ratio of $WW \rightarrow l\nu jj$ is 6 times larger than $WW \rightarrow l\nu l\nu$.
- It has a huge QCD *W+jets* background.
- We can take advantage of the decay kinematics of the Higgs (spin=0) in reducing background.
- Finally compose Likelihood discriminant for S/B separation.
- - Angular distribution between lepton and down type jet.
- - Dijet mass, reconstructed higgs mass, ...

W Decay Mode
$l\nu$ ~ 10 %
ud, cs ~ 30 %



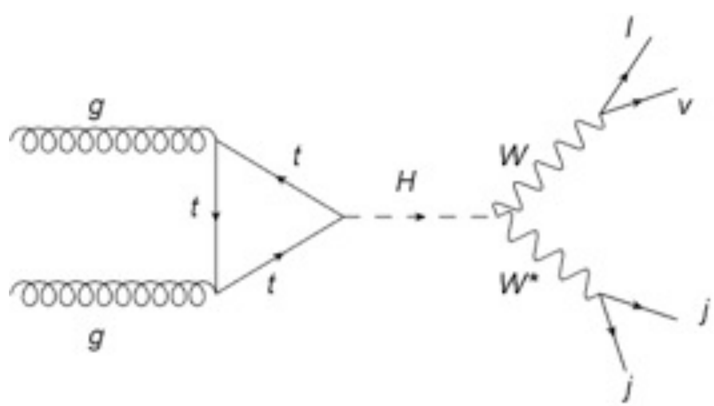
$H \rightarrow WW \rightarrow l\nu jj$ and $H \rightarrow WW \rightarrow l\nu l\nu$ by Comparison

$H \rightarrow WW \rightarrow l\nu l\nu$

- Easy to obtain very clean search sample.
  - Backgrounds: dibosons (*WW*, *WZ*, *ZZ*) , Z/γ^*, tt, $W\gamma$, *W*+jets
- Dominant high mass search mode at CDF.
- 2 neutrinos in the final state
  - Event reconstruction is very difficult.

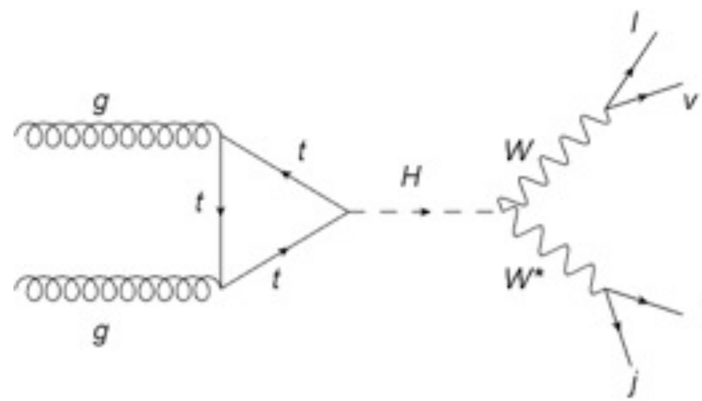
$H \rightarrow WW \rightarrow l\nu jj$

- Challenging to control the huge *W +jets* background.
  - Backgrounds: ***W*+jets**, dibosons (*WW*, *WZ*, *ZZ*), single top, tt, non-*W*
- Addition of this mode will enhance CDF sensitivity.
- 1 neutrino in the final state
  - mass reconstruction not too hard.



Event Selection

- Using 4.6 fb^{-1} of data.
- Signal topology: *H* → *WW* → *lvjj*
- Event Selection:
  - One electron or muon
    - E_T (p_T) > 20 GeV, $|\eta|<1$
  - MET > 20 GeV
  - Exact 2 jets
    - E_T > 20 GeV, $|\eta| < 2.0$
  - $60 < M_T(l, MET) < 100$ GeV

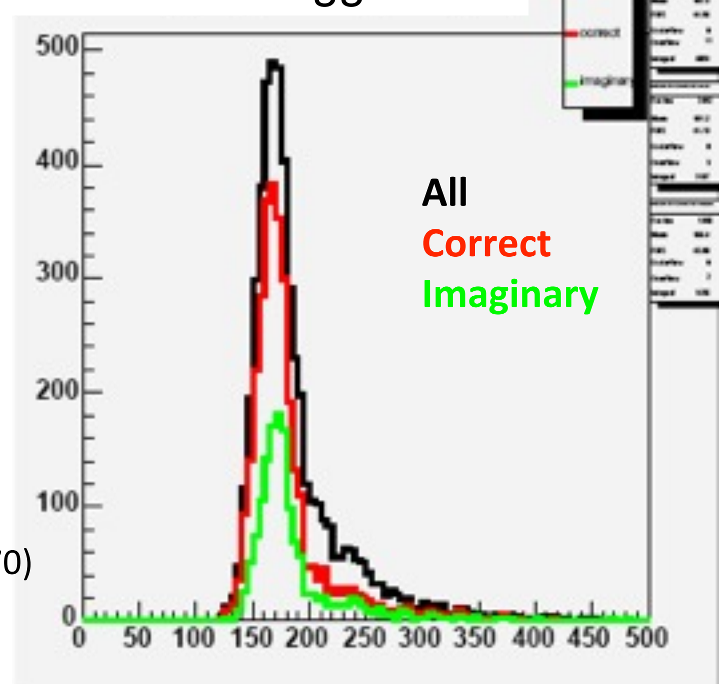


p_z^ν Reconstruction (1)

- Can't measure p_z^ν in a hadron collider!!
- We solve this equation:

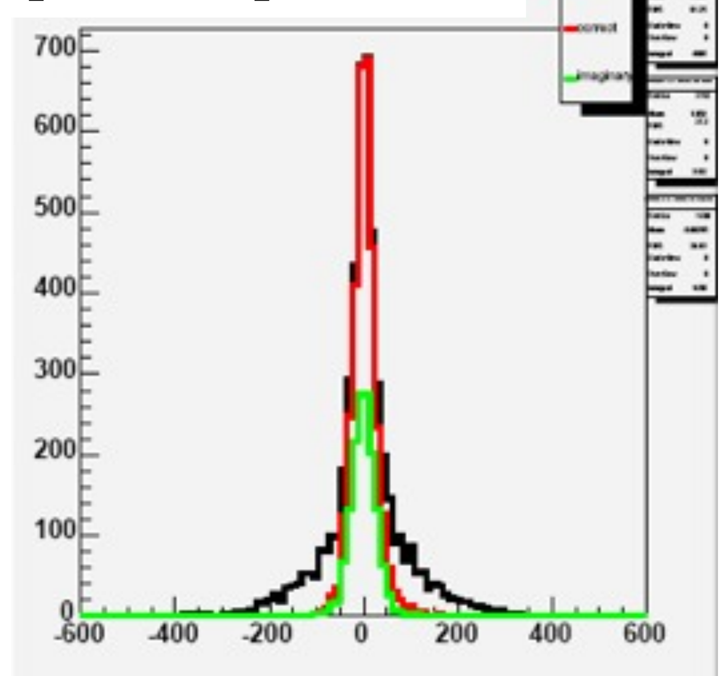
  $m(e,\nu) = m_W$ (=80.419 GeV).
- Pick up the solution with smaller absolute value $|p_z^\nu|$.
- Take the real part for events with imaginary solution.

Reconstructed Higgs Mass



(Input m_H=170)

$|p_z^\nu(\text{reco})|-|p_z^\nu(\text{MC truth})|$



p_z^ν Reconstruction (2)

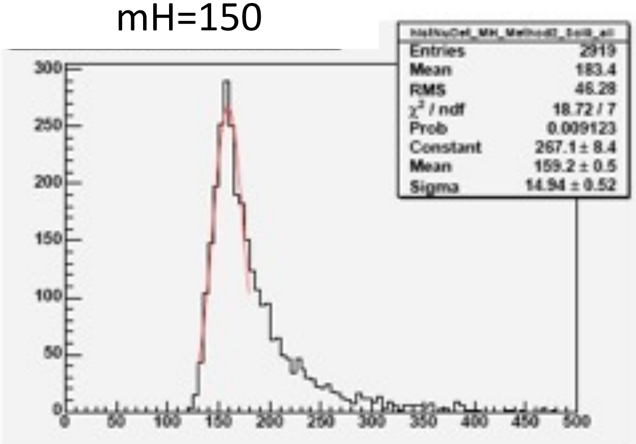
- Some results of the reconstruction method:

input m_H	imaginary solution	correct fraction	mass resolution(GeV)
150	16%	62%	14.9
170	30%	49%	14.4
200	31%	48%	21.9

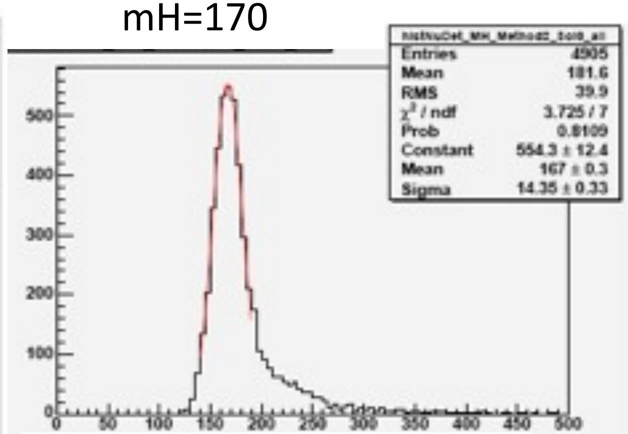
Correct : the picked solution is closer than another to MC truth p_z value.

- Fit of Reconstructed Higgs Mass to Gaussian:

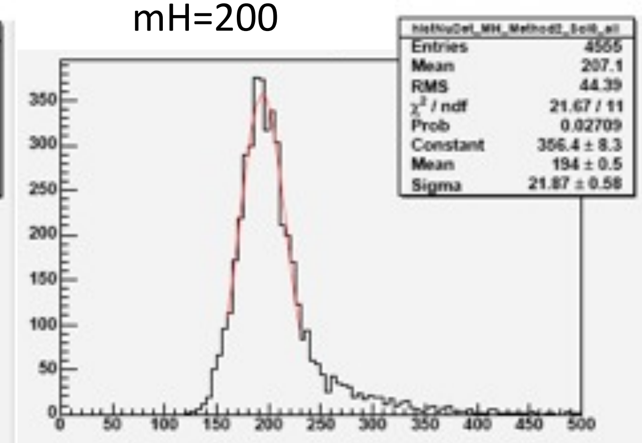
mH=150



mH=170



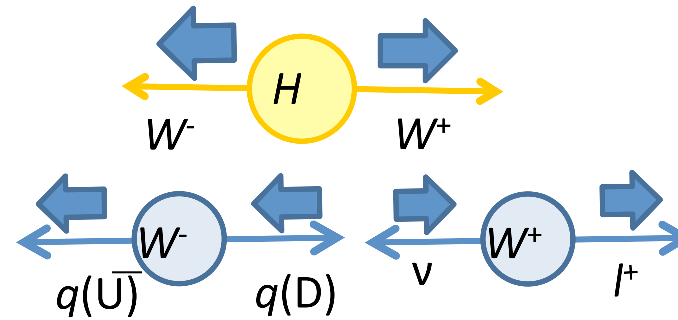
mH=200

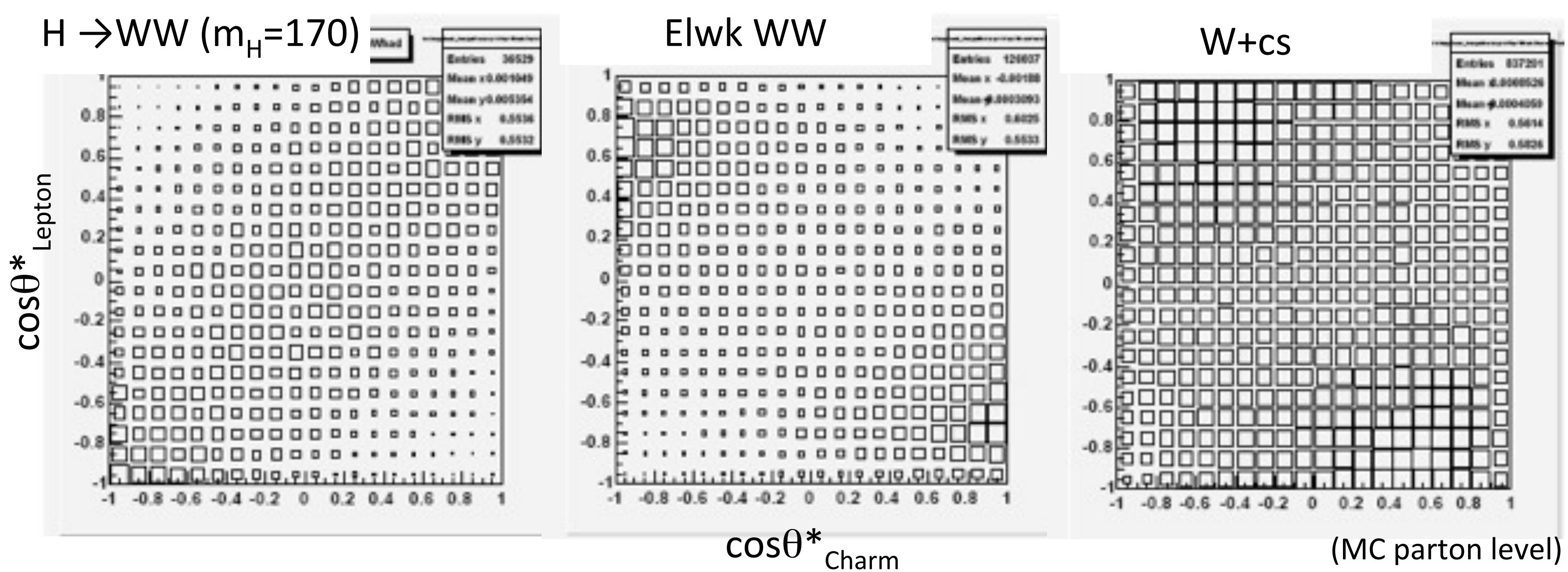


Reconstructed Higgs Mass (GeV)

Higgs Spin Properties (1)

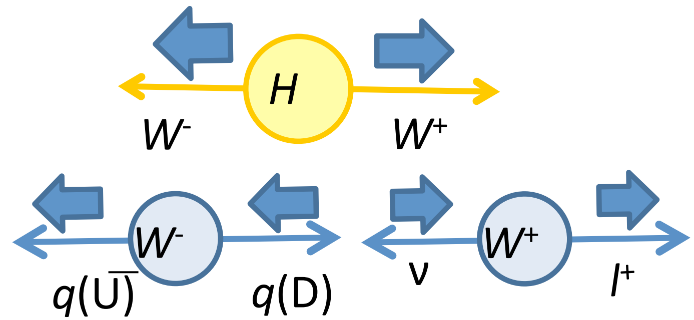
- Higgs spin=0 results in strong angular correlation between the lepton and up/down-type jet.
- This kinematic properties provide a strong tool to reject background.

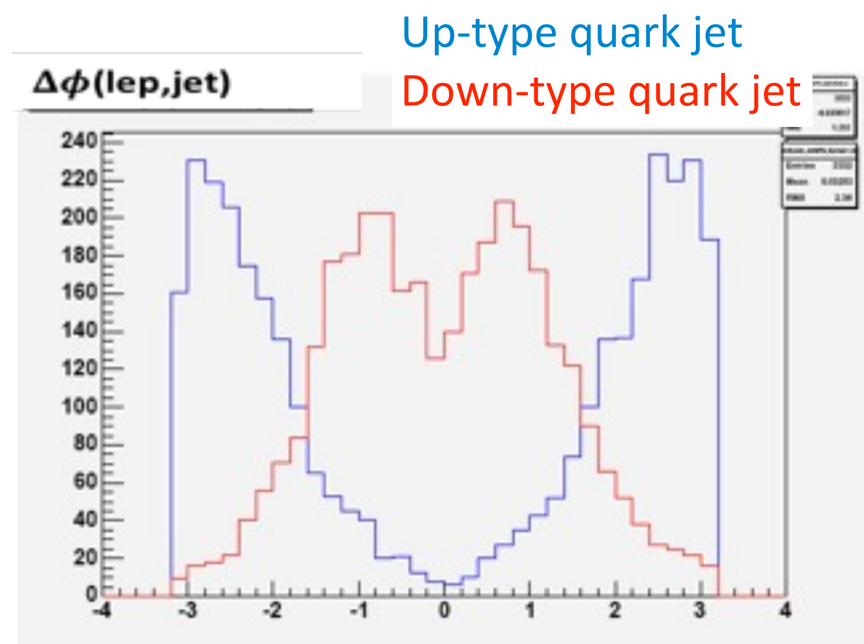




Higgs Spin Properties (2)

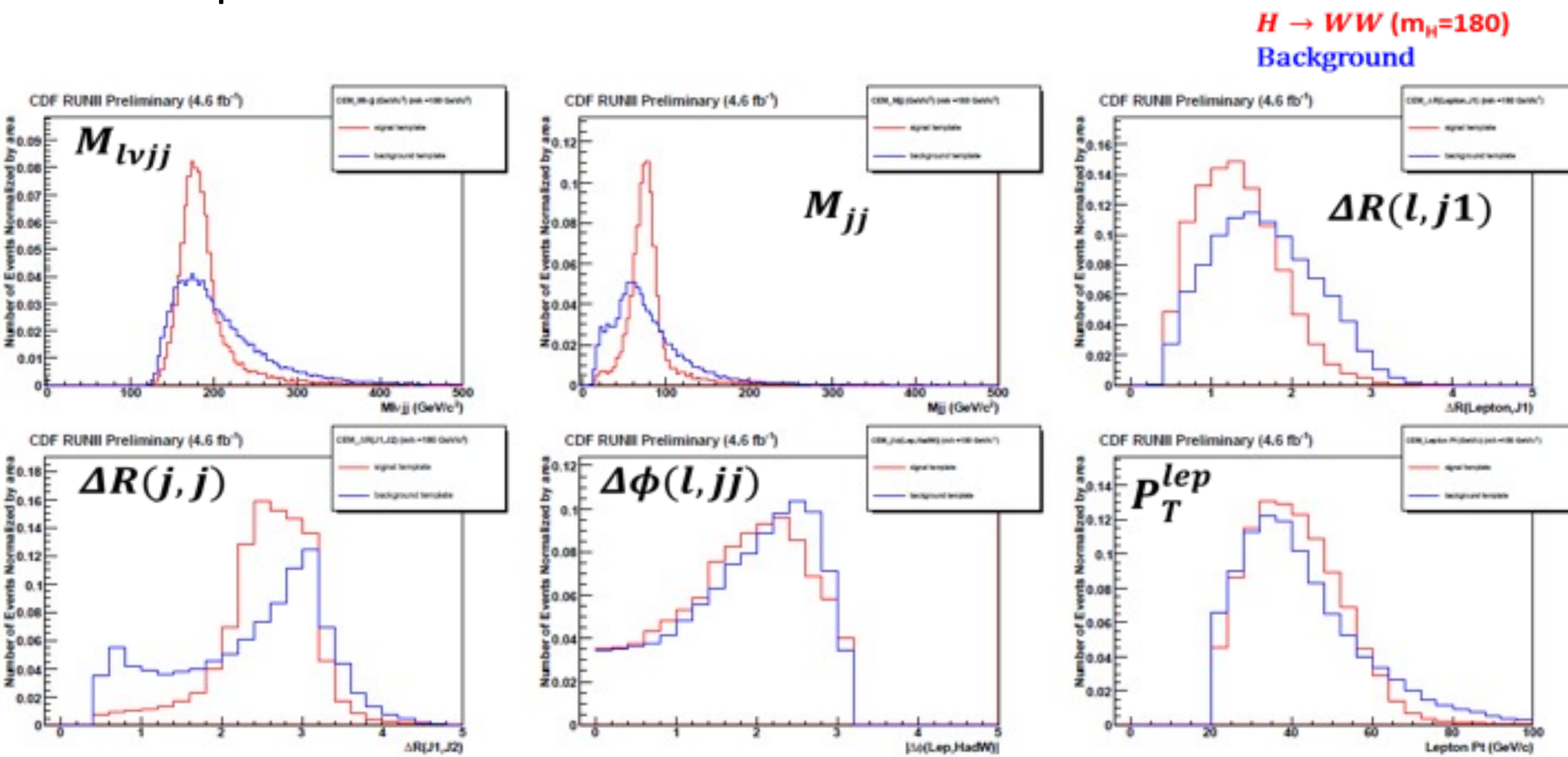
- We tag the jet closer to lepton in $\Delta\phi$ as down-type jet.
- Such a jet-parton assignment reconstructs the event correctly 88.4% of the time.





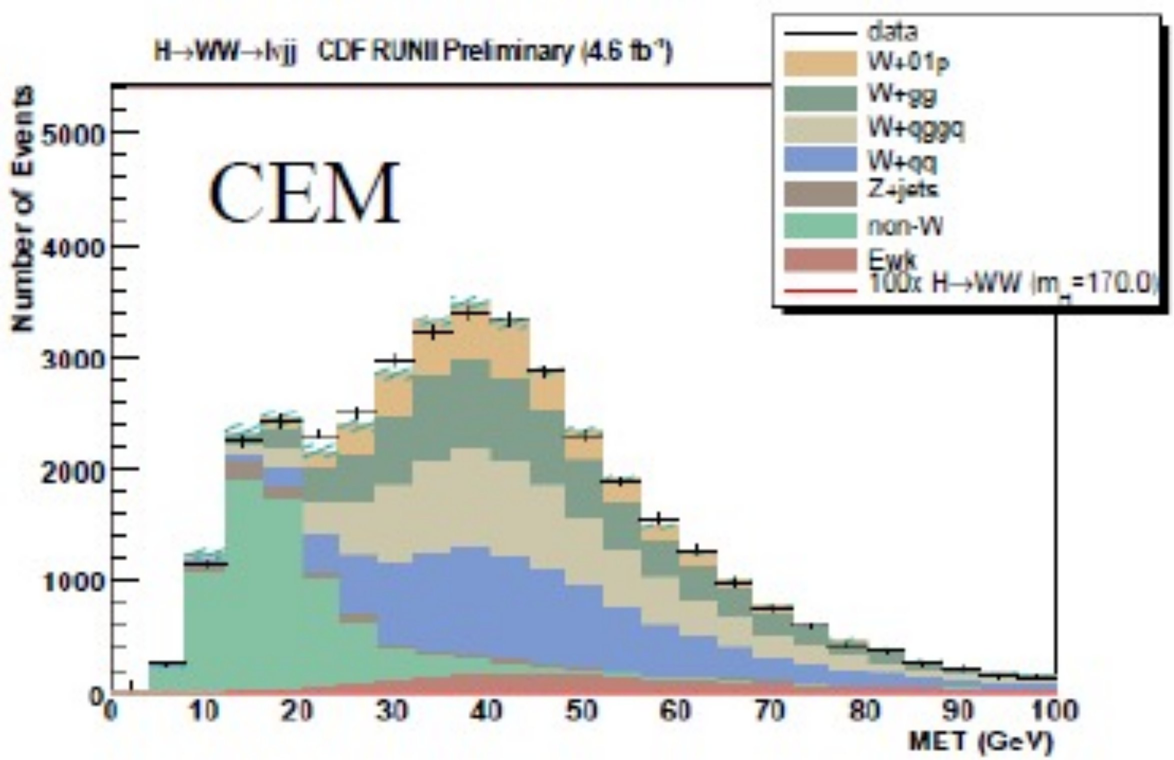
Likelihood Composition

- We compose a likelihood discriminant using six kinematic variables, in order to improve the S/B separation.
- We used *W+2 jet* MC events to model the background template.



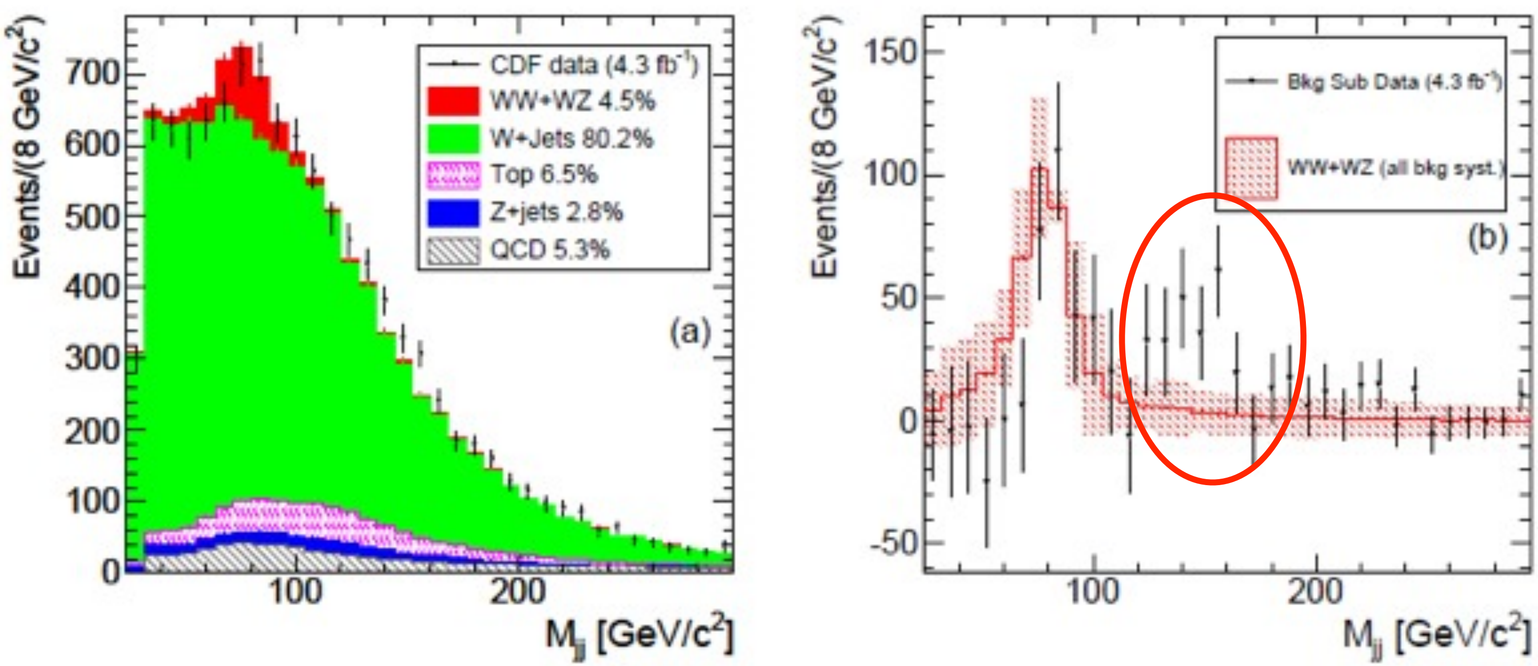
Background Estimation (1)

- At CDF, we usually normalize QCD multijet and W+jets backgrounds by fitting the MET distribution to data.
  - QCD multijet shape is modeled with data.
  - W+jets shape is modeled by ALPGEN.



Problem of W+jets bkgd description

- We were having a problem describing the W+2jets events before b-tagging.



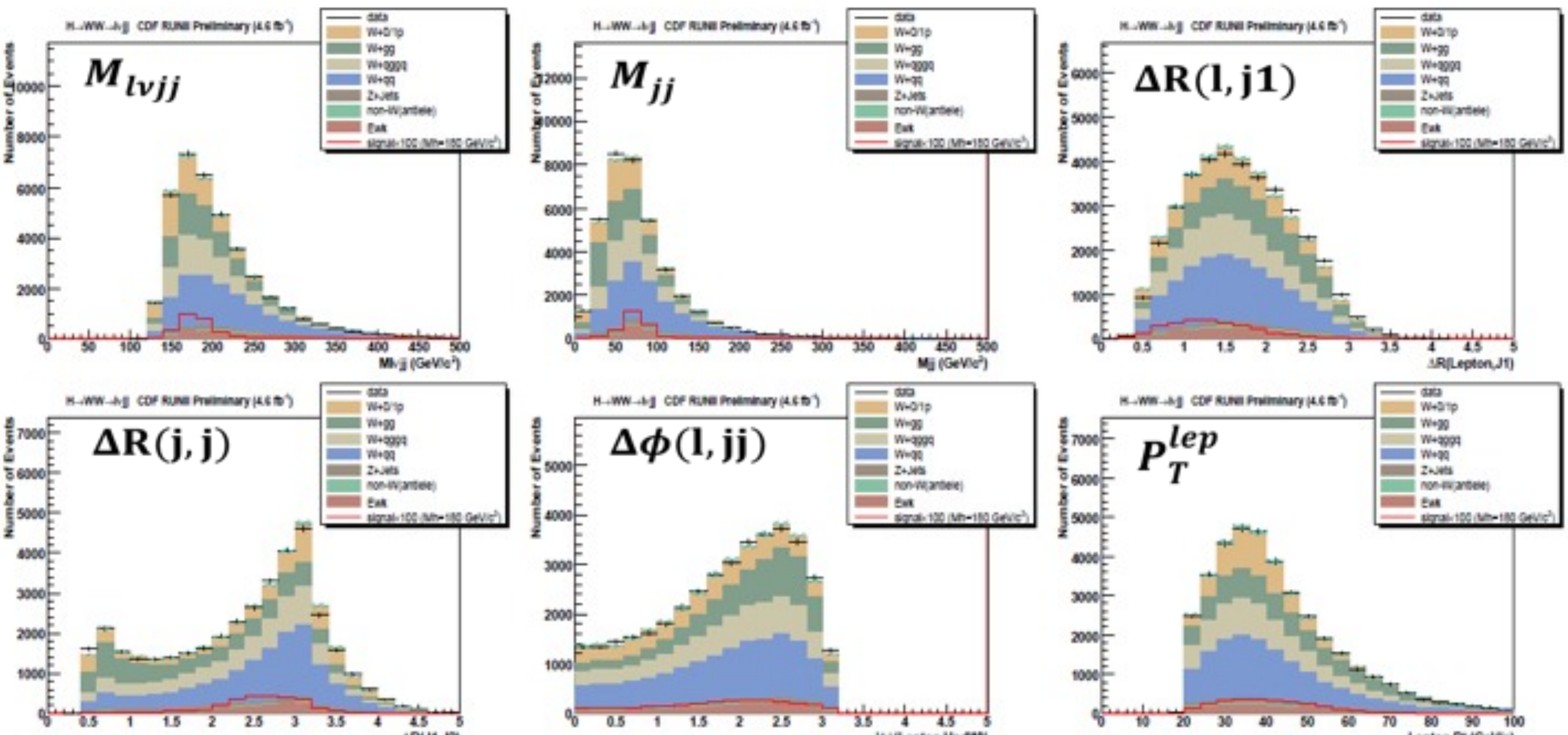
Phys.Rev.Lett.106:171801,2011
"Invariant Mass Distribution of Jet Pairs Produced in Association with a *W* boson in $p\overline{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV"

Background Estimation (2)

- MET fit to obtain crude W+jets/QCD normalization.
- Fit the final likelihood discriminant to data with signal and each background fluctuated within stat. and syst. uncertainties.
  - Break down W+jets into W+qq/W+qg/W+gg, and each subprocess is floated independently.
  - # signal events is also fluctuated.
    - The fit returned zero-consistent signal contribution this time.
  - Systematic uncertainties are taken into account in the fit, including JES and Q^2 of W+jet subprocess.

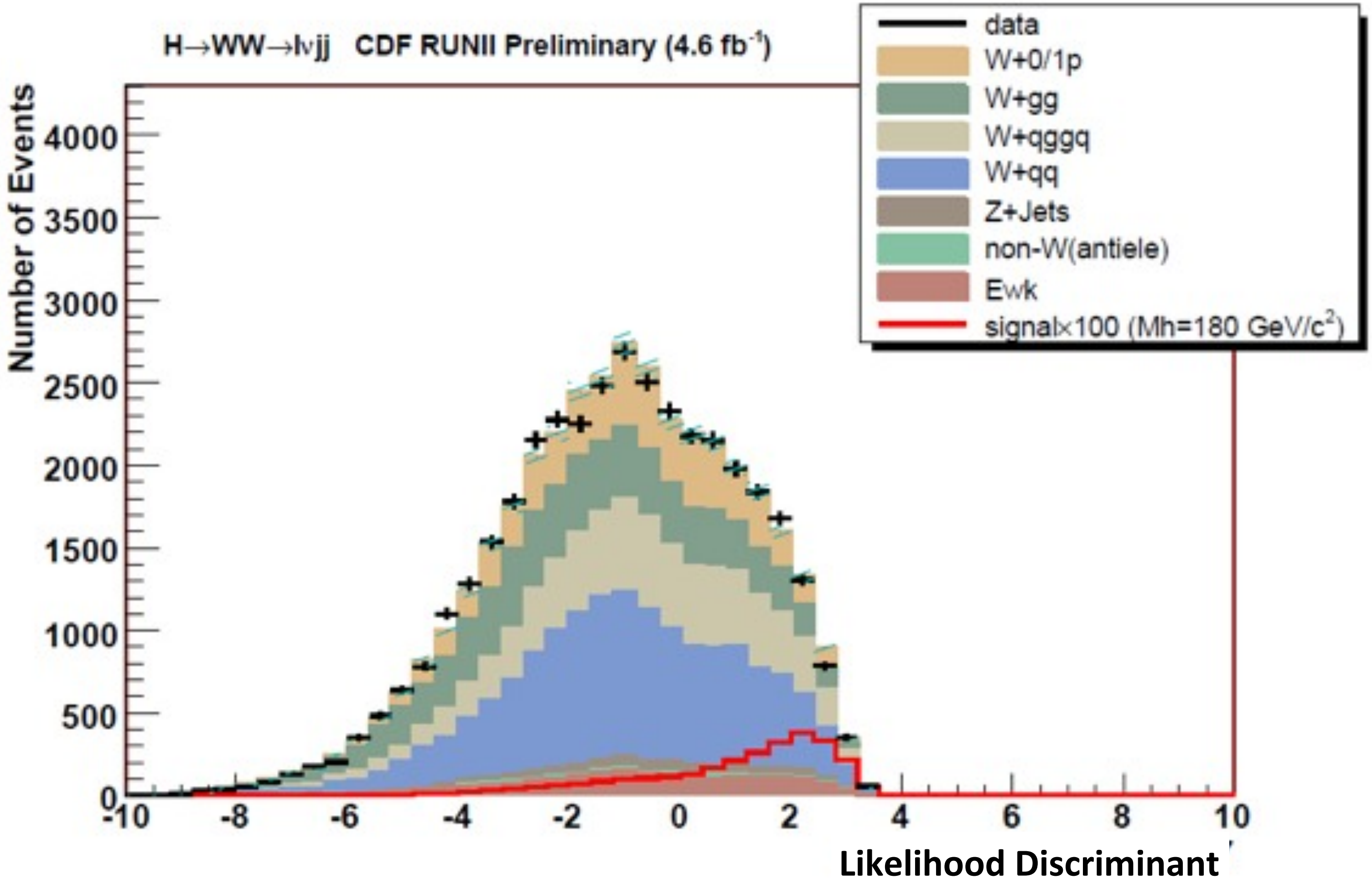
Input Variables to Likelihood Discriminant

- Data-MC agreement with this background estimation is good for these kinematic variables!
  - Some other unused variables (**jet Et**, jet η, Mt(l,MET)) still suffer discrepancy, though improved by this procedure.



Open red histograms show 100xsignal for m_H=180 GeV/c^2.

Likelihood Discriminant



Open red histogram shows 100xsignal for m_H=180 GeV/c^2.

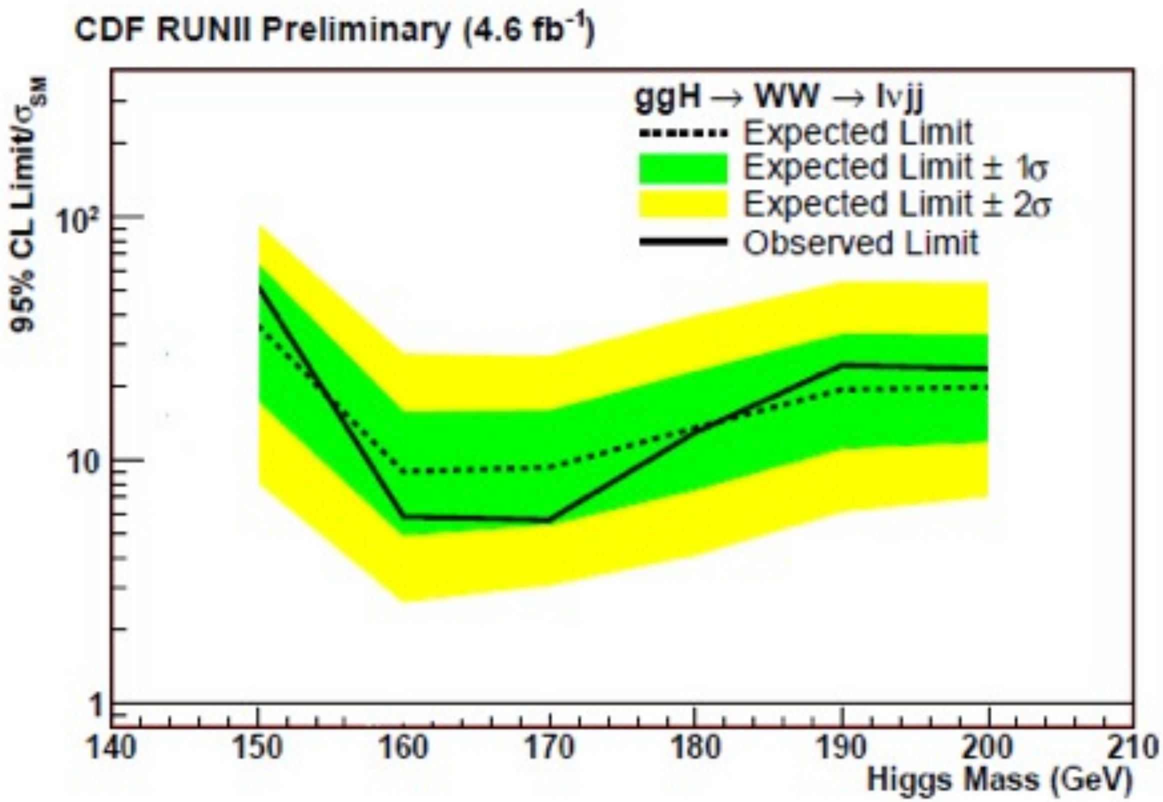
Systematics Table

CDF RUNII Preliminary (4.6 fb^{-1})

Systematic Uncertainty (%)	signal	Electroweak	W+qq	W+qg/gq	W+gg	W+0/1p	Z+LF	non-W
Luminosity (CDF)	4.4	4.4					4.4	
Luminosity (Tevatron)	3.8	3.8					3.8	
Trig. Eff., Lepton ID	2	2					2	
Ewk Cross Section		6						
Signal cross section								
Scale inclusive	13.4							
Scale1+Jet	-23							
Scale2+Jet	0							
PDF	7.6							
ISR/FSR	2.7							
Jet Energy Scale	$3 \sim 8$	2						
W+qq Normalization			20					
W+qg/gq Normalization				20				
W+gg Normalization					20			
W+0/1 parton Normalization						20		
W+jets JES quark $+1\sigma$			$+0.6$s	-2.8s	-5.5s	$+19.4$s		
W+jets JES quark -1σ			-2.0s	$+2.1$s	$+5.8$s	-12.6s		
W+jets JES gluon $+1\sigma$			-8.5s	-0.5s	$+7.0$s	$+15.3$s		
W+jets JES gluon -1σ			$+9.1$s	-0.7s	-9.0s	-9.0s		
W+jets Q^2 shape $Q^2 = 2.0$			$+0.2$s	-6.1s	$+0.8$s	$+22.9$s		
W+jets Q^2 shape $Q^2 = 0.5$			$+0.7$s	$+9.7$s	-4.1s	-34.3s		
Z+jets Normalization							39.5	
non-W Normalization								40

Systematics that also affect the background shape

Higgs Cross Section Limit with $H \rightarrow WW^{(*)} \rightarrow l\nu jj$ Channel 4.6 fb^{-1}



- Excludes $\sigma(gg \rightarrow H) > 9.0 \times \sigma_{SM}$ at 95% C.L for m_H=160 GeV/c^2.
- Excludes $\sigma(gg \rightarrow H) > 19.9 \times \sigma_{SM}$ at 95% C.L for m_H=200 GeV/c^2.
- Our student obtained his ph.D with these results.

Summary

- We searched for $H \rightarrow WW \rightarrow l\nu jj$ in 4.6 fb^{-1} data obtained in CDF Run II.
- Our analysis composed a likelihood discriminant from six kinematic variables, in order to improve the sensitivity.
- We set an upper limit on the production cross section of the Higgs boson:
  - $\sigma(gg \rightarrow H) < 9.0 \times \sigma_{SM}$ for $m_H = 160$ GeV/c^2 (95% C.L).
  - $\sigma(gg \rightarrow H) < 19.9 \times \sigma_{SM}$ for $m_H = 200$ GeV/c^2 (95% C.L).

backup

Likelihood Discriminant

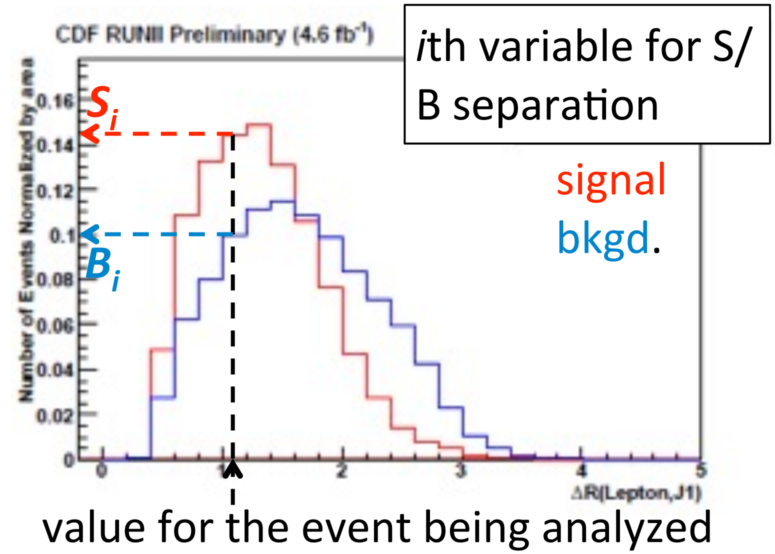
- $H \rightarrow WW^{(*)} \rightarrow l\nu jj$ analysis composes a likelihood discriminant from 6 kinematic variables in order to improve Signal/Background separation.
  - Signal template is modeled by PYTHIA Higgs sample, and background is modeled by ALPGEN W+2jet sample.

- For an event with a value for *i*th variable as shown in right plot, the likelihood for this single variable is defined as: $L_i = \dfrac{S_i}{B_i}$

- The likelihood discriminant is defined as:

$$\log L = \sum_i \log L_i = \sum_i \log\left(\frac{S_i}{B_i}\right)$$

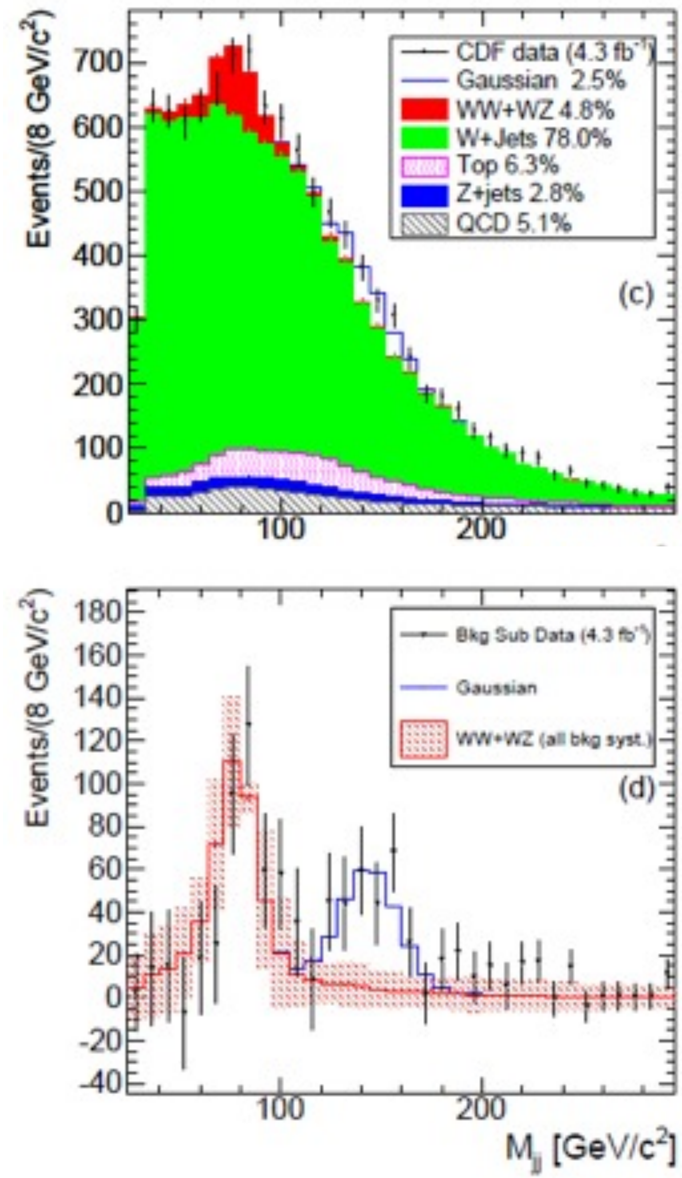
(*i* runs through all the variables considered in the likelihood composition)



Dijet Mass Spectrum in $l\nu jj$ Final State

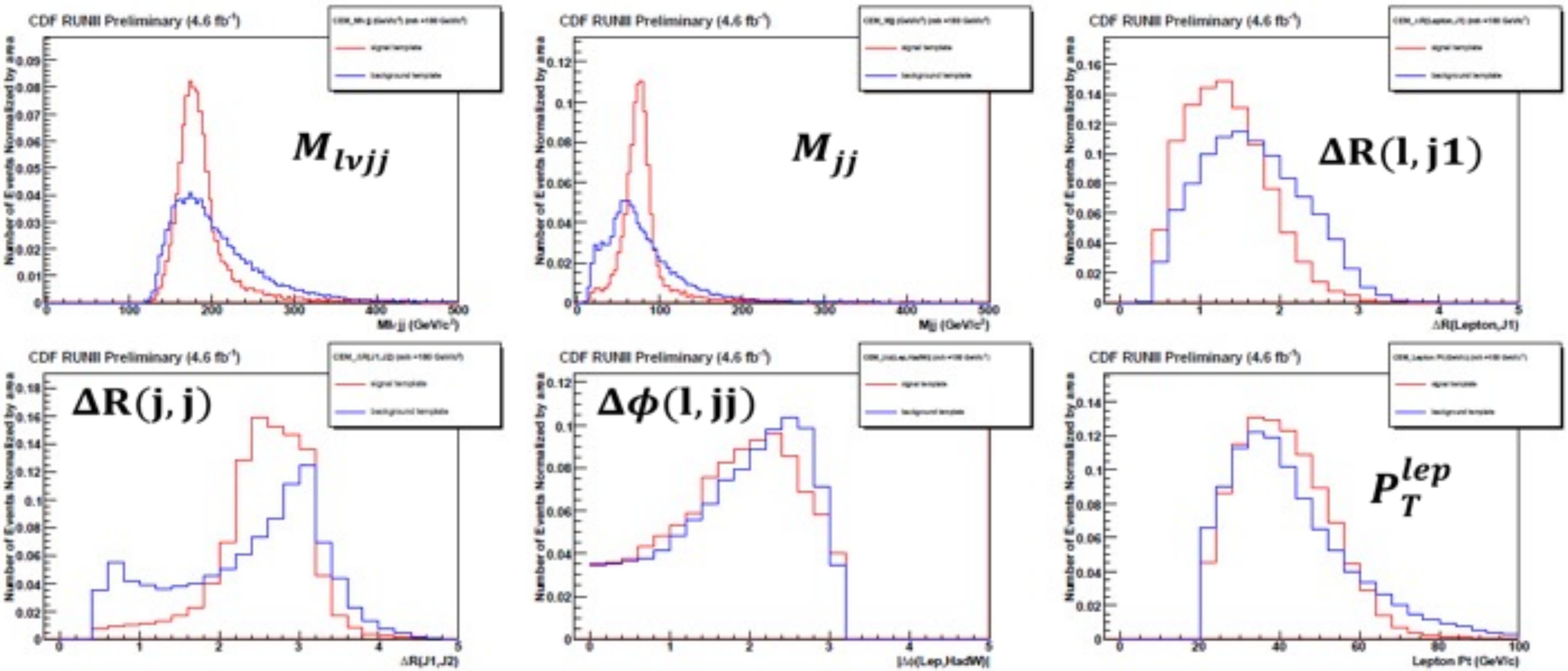
- **Spring 2011 analysis using 4.3 fb^{-1}.**
  - e/μ with Pt>20 GeV , $|\eta|$<1.
  - MET>25 GeV.
  - 2 jets with Et>30GeV , $|\eta|$<2.4.
  - Mt(e,MET)>30 GeV.
  - $\Delta\phi$(MET,j1)>0.4.
  - Pt(jj)>40 GeV.

- An excess is seen.
- 3.2σ deviation from estimated background, after considering the systematic uncertainties on background modeling.



Likelihood Templates for CEM

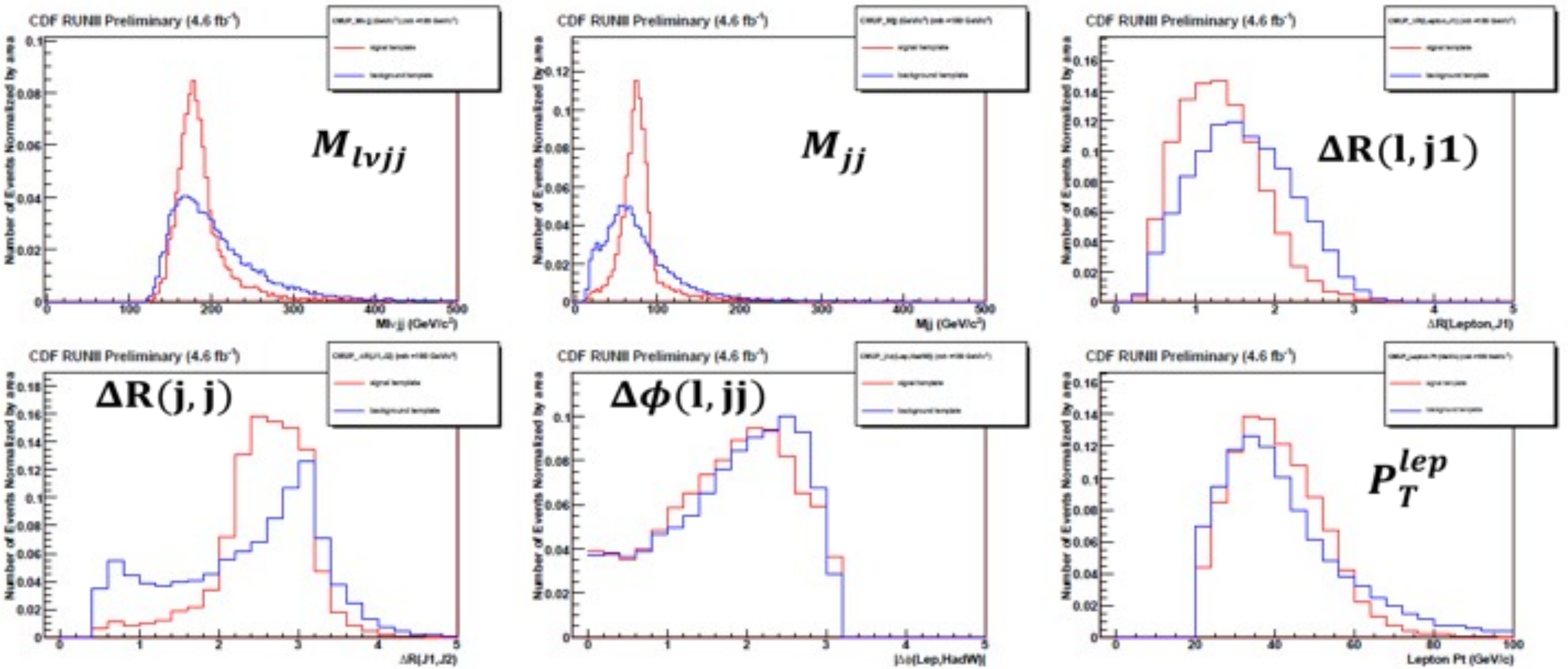
- Signal and background templates for central electron ($|\eta| < 1$).
- For m_H=180 GeV/c^2.



In the presentation is the CEM one.

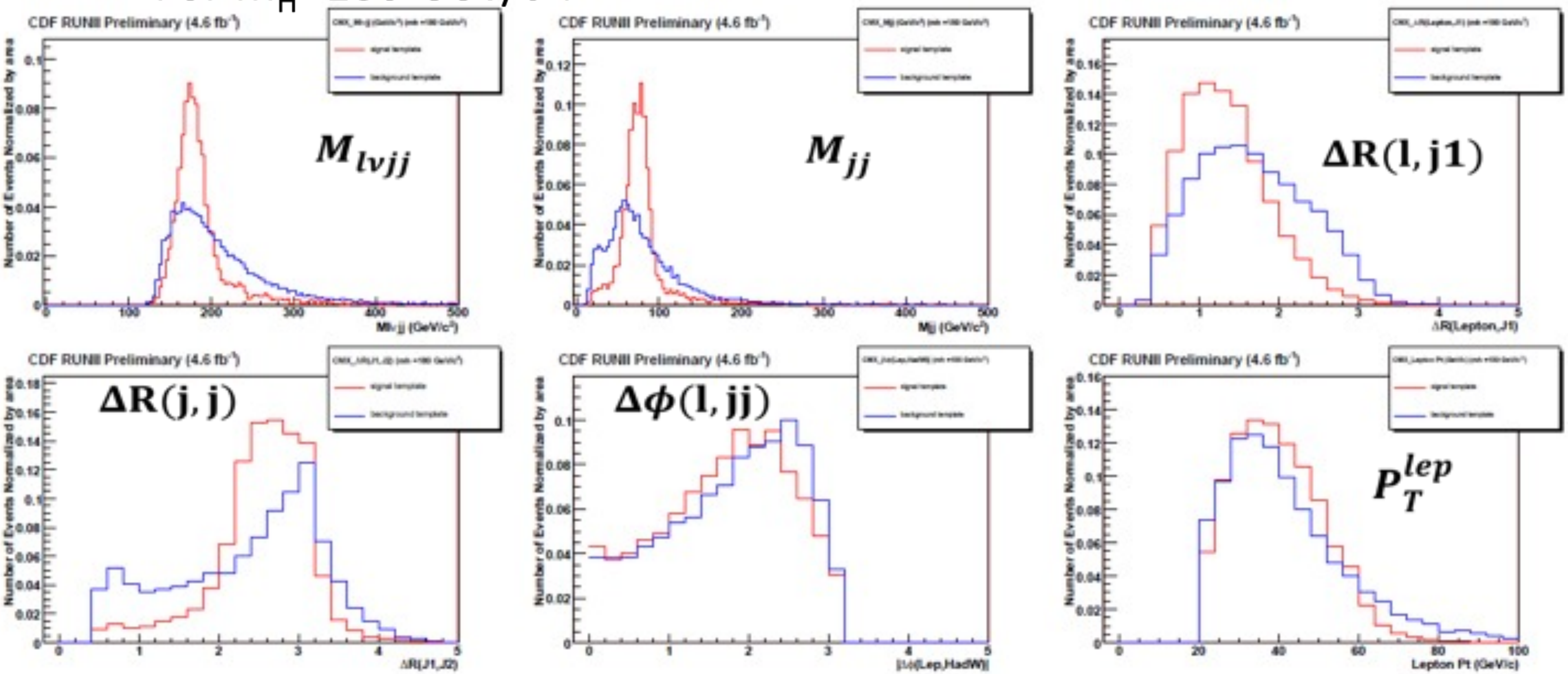
Likelihood Templates for CMUP

- Signal and background templates for central muon ($|\eta| < 0.6$).
- For m_H=180 GeV/c^2.



Likelihood Templates for CMX

- Signal and background templates for intermediate muon (0.6<$|\eta| < 1.1$).
- For m_H=180 GeV/c^2.



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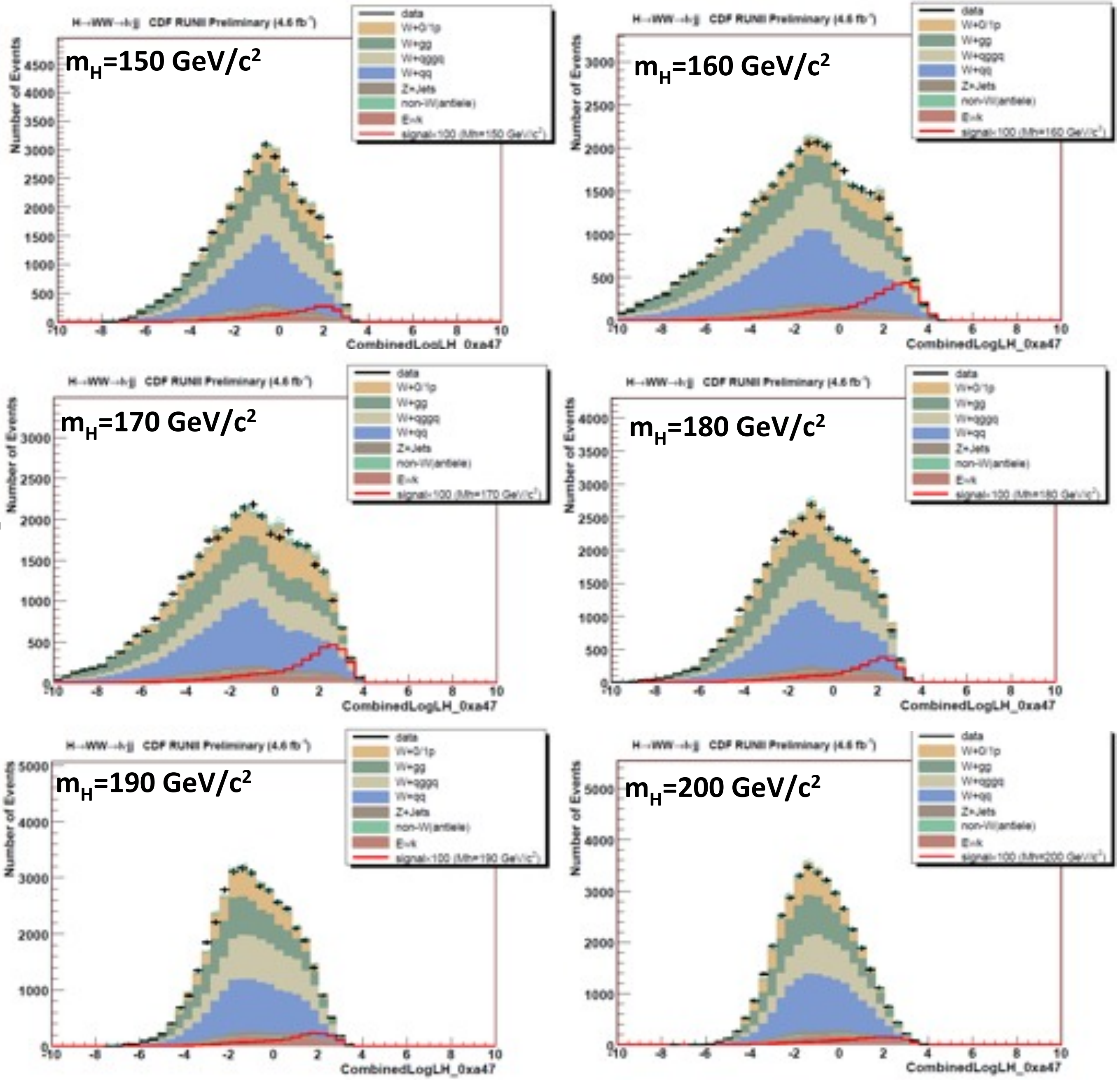


m_H=150 GeV/c²
m_H=160 GeV/c²
m_H=170 GeV/c²
m_H=180 GeV/c²
m_H=190 GeV/c²
m_H=200 GeV/c²
Number of Events
CombinedLogLH_0xa47
CDF RUNII Preliminary

Background Summary

Estimated number of background:

CDF RUN II Preliminary (4.6 fb^{-1})

process	# events
Ewk	1884 ± 166
non-W QCD	325 ± 122
$Z + jets$	880 ± 345
$W + qq$	12912 ± 1453
$W + qg/gq$	7712 ± 1045
$W + gg$	7788 ± 452
$W + 0/1p$	6180 ± 918
Total Background	37685 ± 2101
Observed	37670

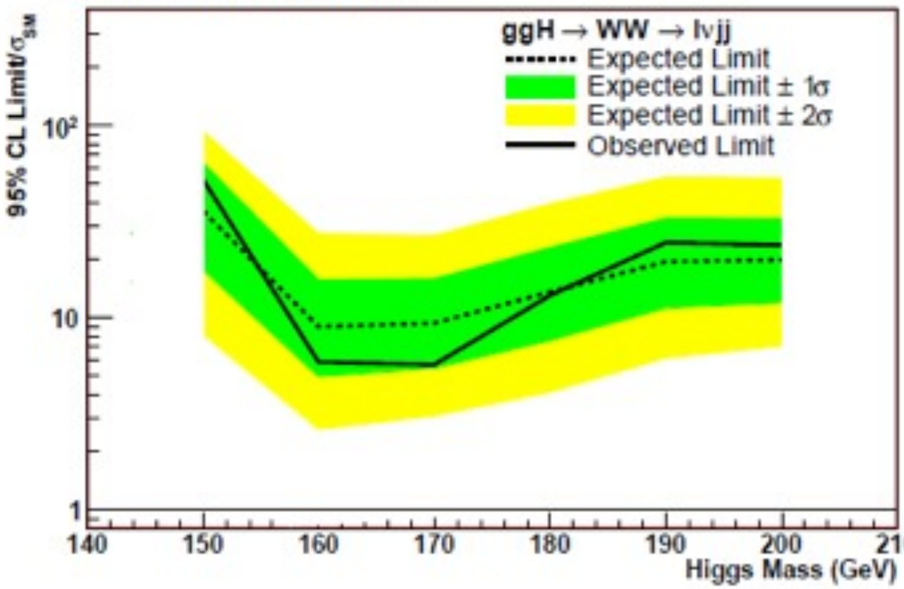
Expected signal yield:

CDF RUNII Preliminary (4.6 fb^{-1})

Higgs Mass (GeV/c^2)	150	160	170	180	190	200
Expected number of events	22.0 ± 6.5	38.6 ± 11.1	36.1 ± 10.3	28.0 ± 8.0	18.9 ± 5.4	14.9 ± 4.3

Higgs Cross Section Limit with $H \rightarrow WW^{(*)} \rightarrow l\nu jj$ Channel (with Table)

4.6 fb^{-1}



CDF RUNII Preliminary (4.6 fb^{-1})

Higgs Mass (GeV/c^2)	150	160	170	180	190	200
-2σ	8.17	2.62	3.08	4.08	6.15	7.11
-1σ	17.7	4.93	5.44	7.61	11.2	11.9
median U.L./σ_{SM}	35.9	8.97	9.36	13.6	19.5	19.9
$+1\sigma$	63.8	15.6	15.9	23.1	32.7	32.5
$+2\sigma$	93.2	27.2	26.6	38.9	53.6	52.9
Obs. U.L./σ_{SM}	52.5	5.88	5.69	13.0	24.5	23.8