Search for a Standard Model Higgs Boson in H → WW Channel at CDF

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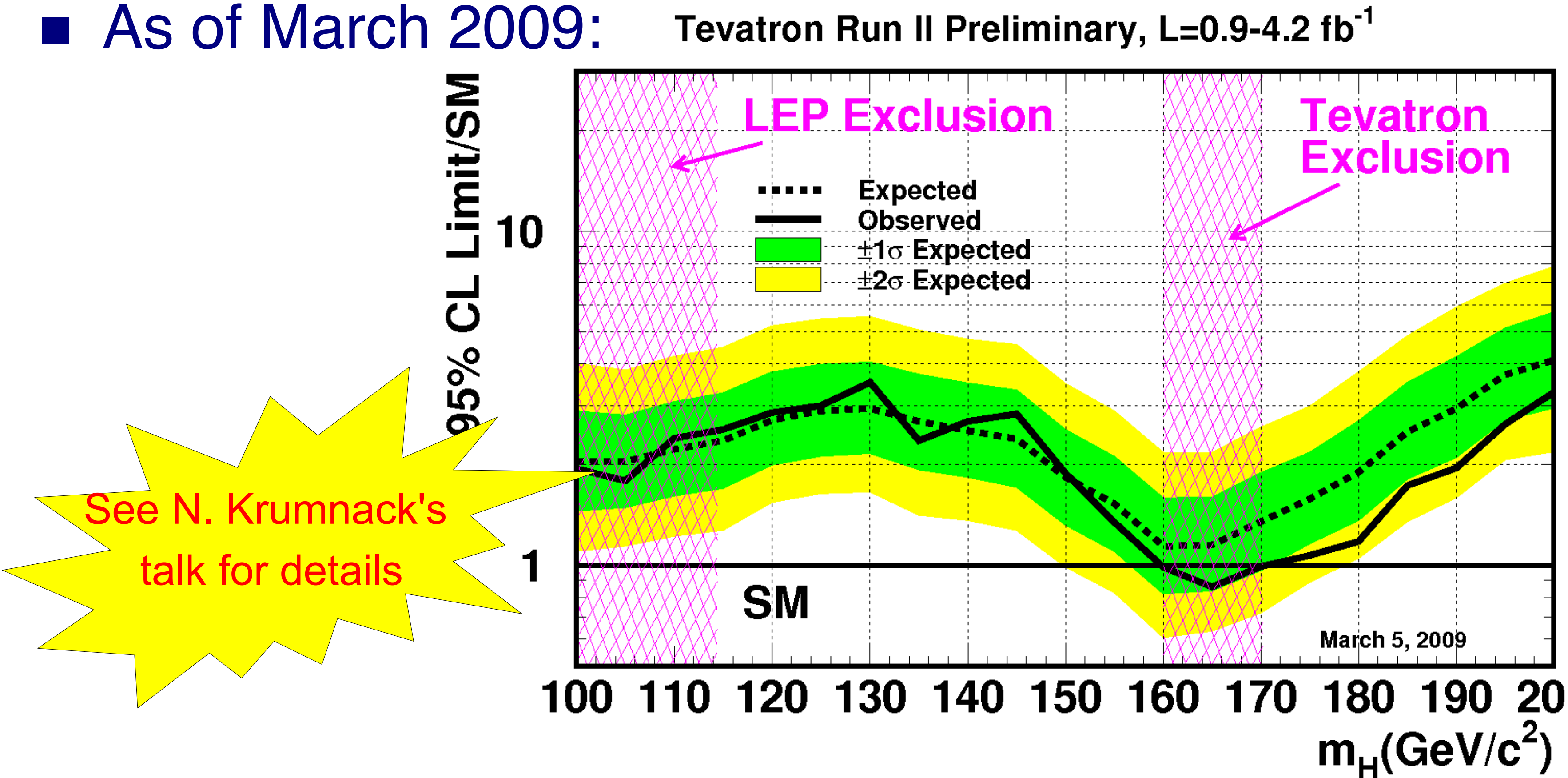
SM Higgs Searches at the Tevatron

- As of March 2009:

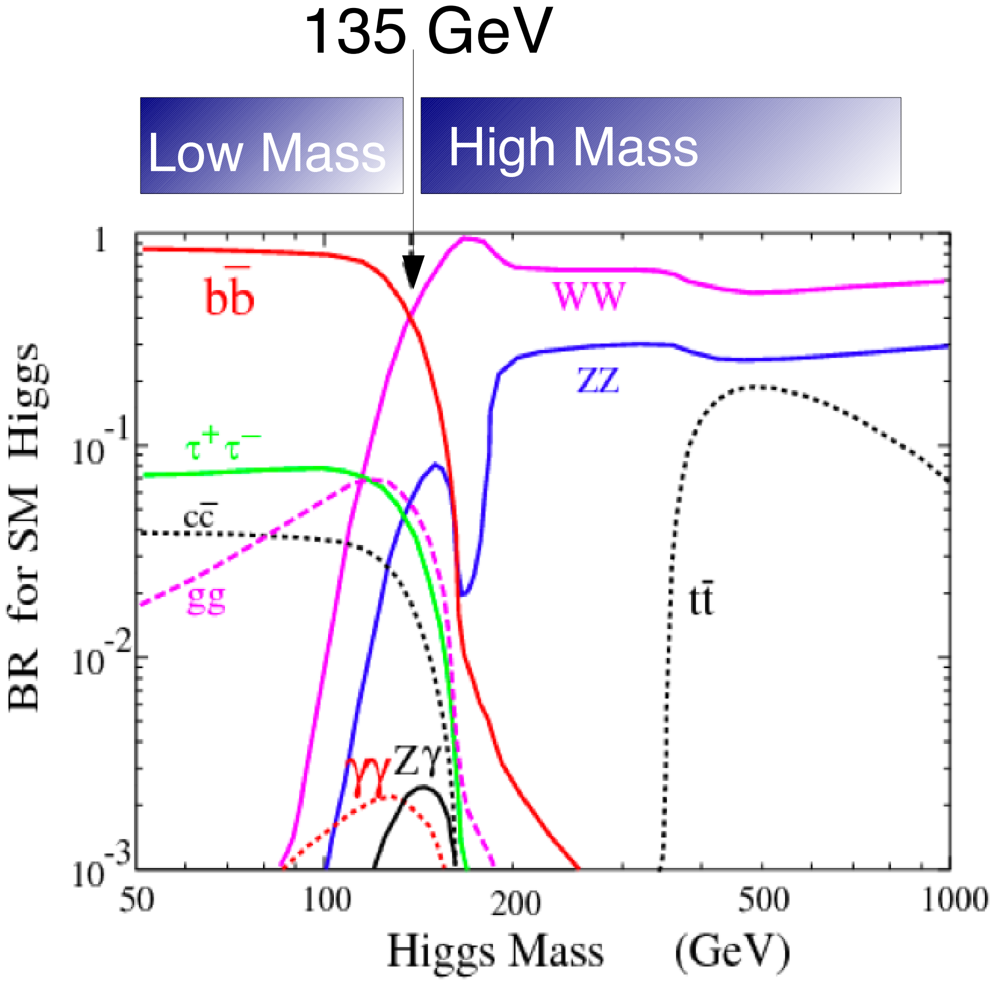


See N. Krumnack's talk for details

- Tevatron goal: continue to expand mass region where sensitive to SM Higgs boson production
  - Today: New CDF result for high mass Higgs using 4.8 fb^{-1}

Standard Model Higgs Decay

- Higgs decay modes depend on Higgs mass m_H
- For gg → H → WW σ x BR,
  - ☐ Peak sensitivity at $m_H \sim 160$
- WW decay modes
  - ☐ Hadronic W decay modes have large QCD bkg
  - ☐ Dilepton (e, μ): BR ~ 6%
    - Small BR, but… clean, easy to trigger
    - Sensitive to τ → (e, μ)
- High mass Higgs search: $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

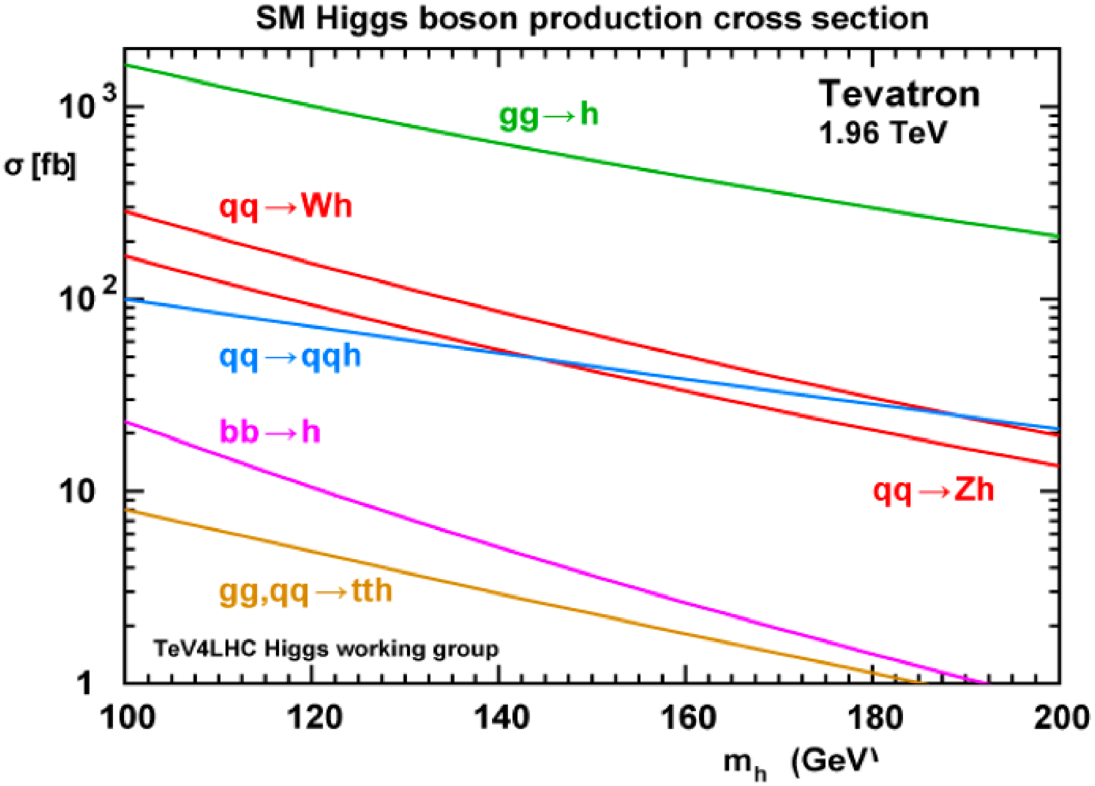

135 GeV

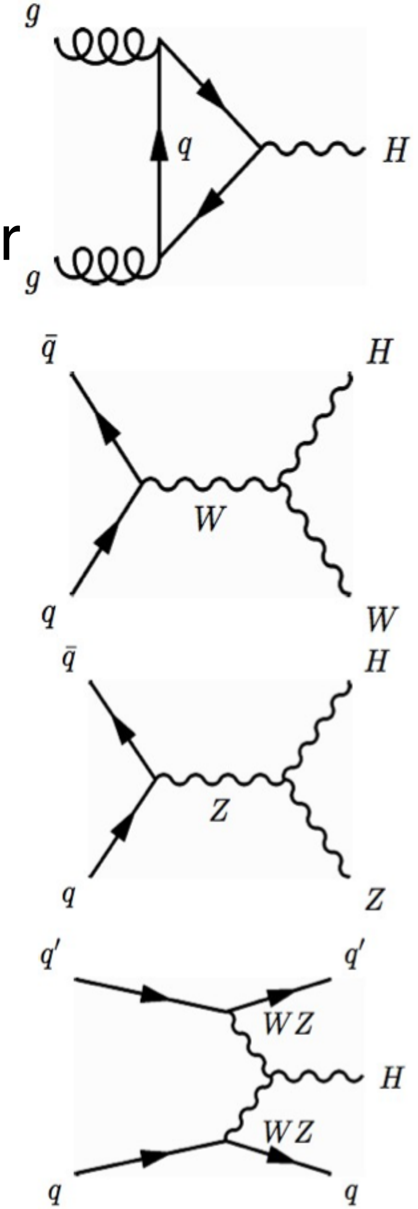
Low Mass

High Mass

Higgs Production at the Tevatron

- Four main production mechanisms
  - ☐ Gluon fusion dominant process at Tevatron
  - ☐ Associated production (WH, ZH) and vector boson fusion give best sensitivity at low m_H

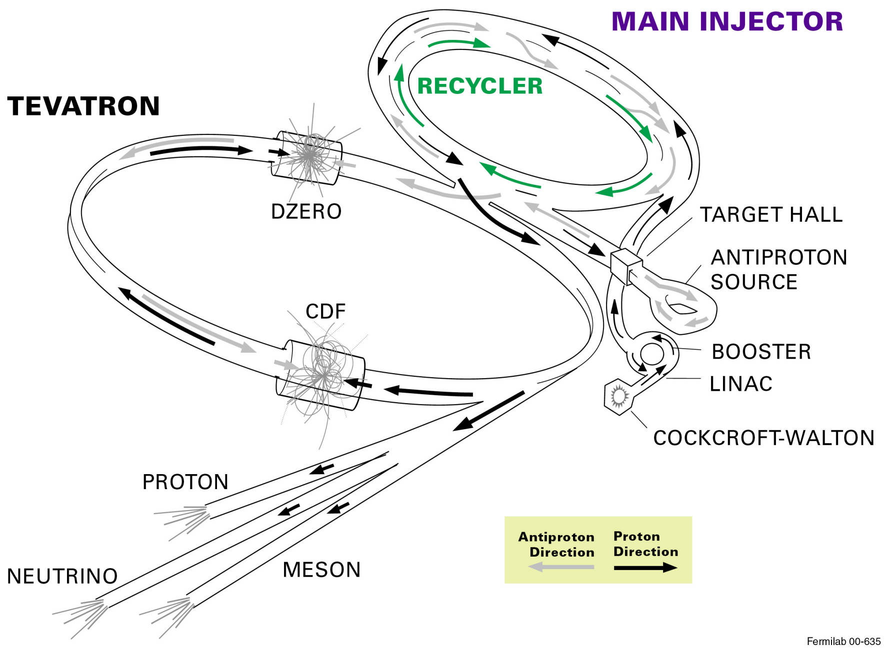

SM Higgs boson production cross section



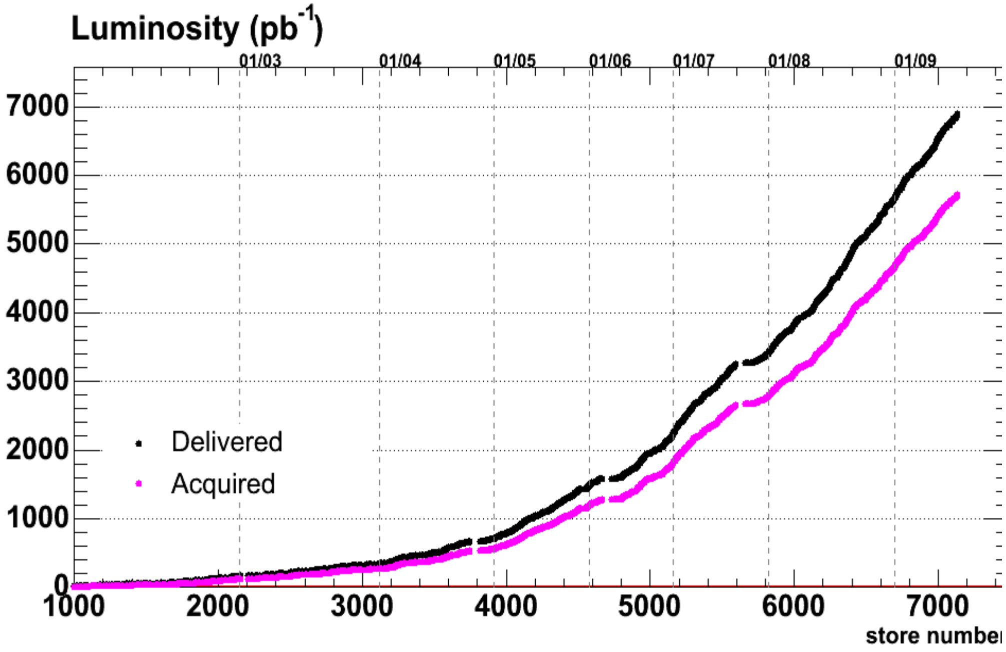
Tevatron Performance

- Collide $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV
- Integrated over 250 pb^{-1} of data in January 2009

FERMILAB'S ACCELERATOR CHAIN



Fermilab 00-635

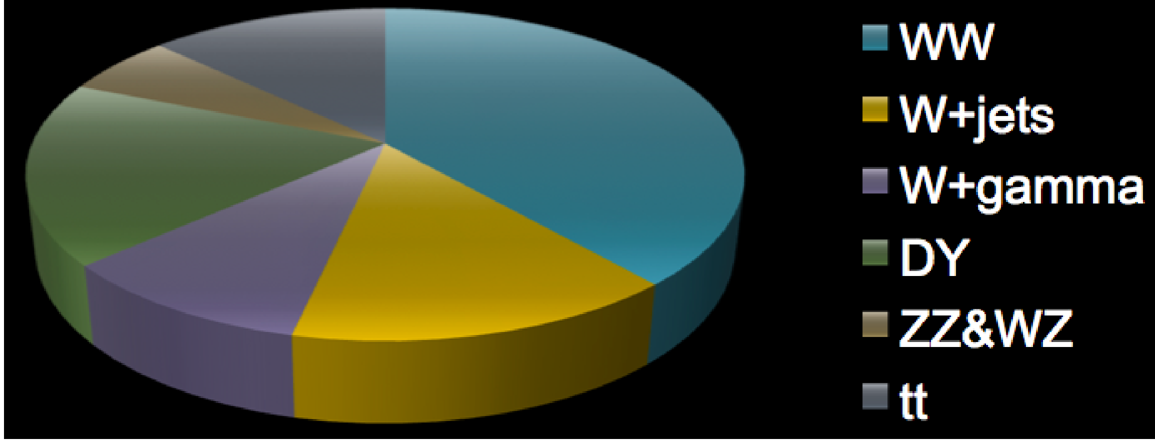


- CDF has acquired about 5.8 fb^{-1} total
  - ☐ Today's results use 4.8 fb^{-1}

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$ Backgrounds

- Standard Model processes create a variety of backgrounds:
- All cross sections measured by Tevatron experiments
  - Many discovery analyses:
    - WW, WZ, ZZ, single top

Background composition:



WW (~40%):
Modeled using MC@NLO MC

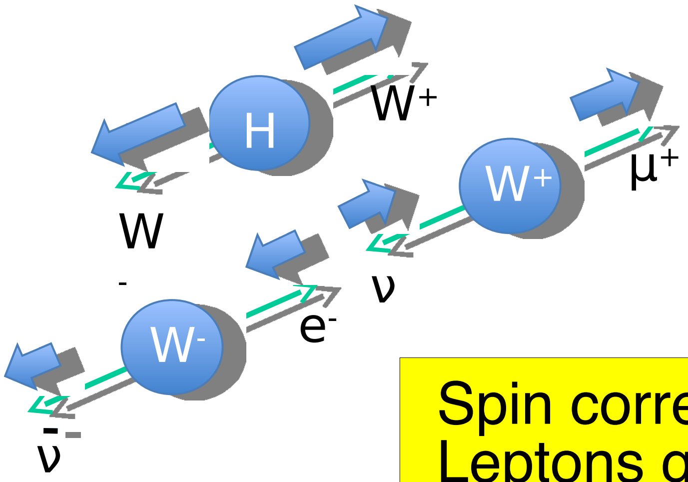
W+jets (~15%):
Data-driven modeling

W+gamma (~10%):
Baur MC

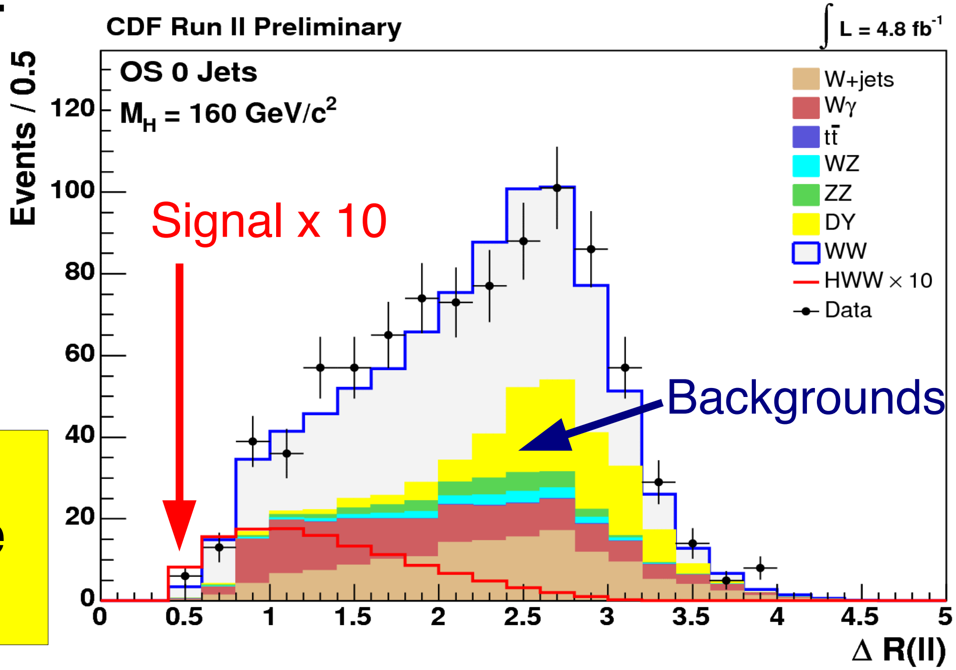
ZZ(3%), WZ(3%), DY (~16%),
tt (~13%) & Signal
Pythia MC

$H \to WW \to \ell\nu\ell\nu$ Signature

- Decay kinematics
  - 2 high p_T leptons (e or μ) with missing transverse energy
  - Broad invariant mass spectrum
  - WW pair from spin-0 Higgs:



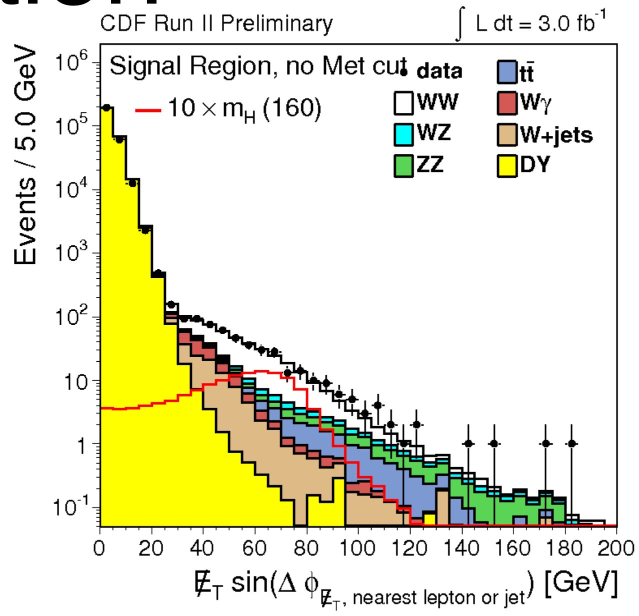
Spin correlation: Leptons go in the same direction

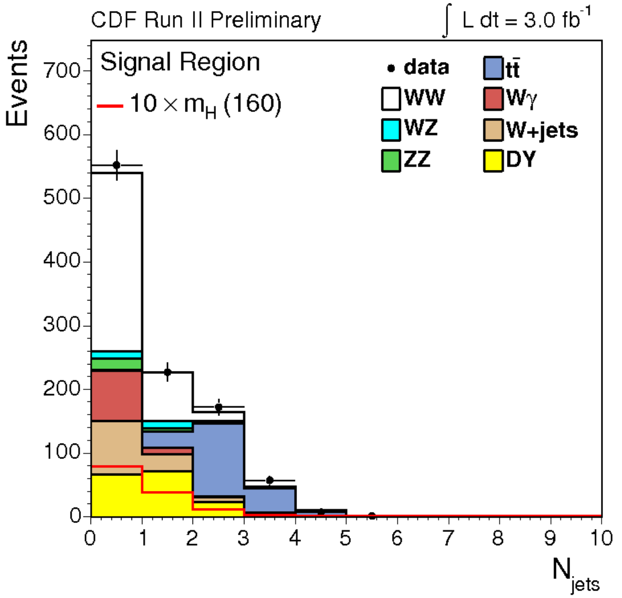


- Dilepton opening angle strongest background discriminant

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$ Selection

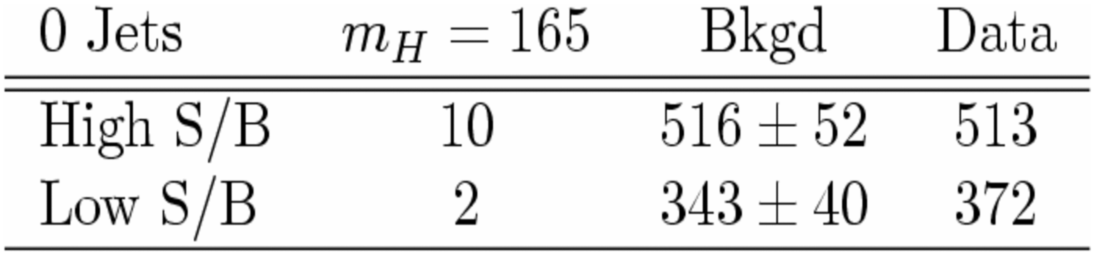
- Trigger on one high-p_T lepton
  - $p_T(\ell_1) > 20$ GeV, $p_T(\ell_2) > 10$ GeV
  - Two opposite charge leptons
  - $M_{\ell\ell} > 16$ GeV/c^2
  - $\not{E}_T^{spec} > 25$ GeV (ee, μμ)
  - $\not{E}_T^{spec} > 15$ GeV (eμ)
- Separate by lepton quality into high and low S/B regions
- Separate analysis by number of jets (0, 1, and ≥ 2) to better optimize signal/background
- Use Neural Networks to separate signal and background





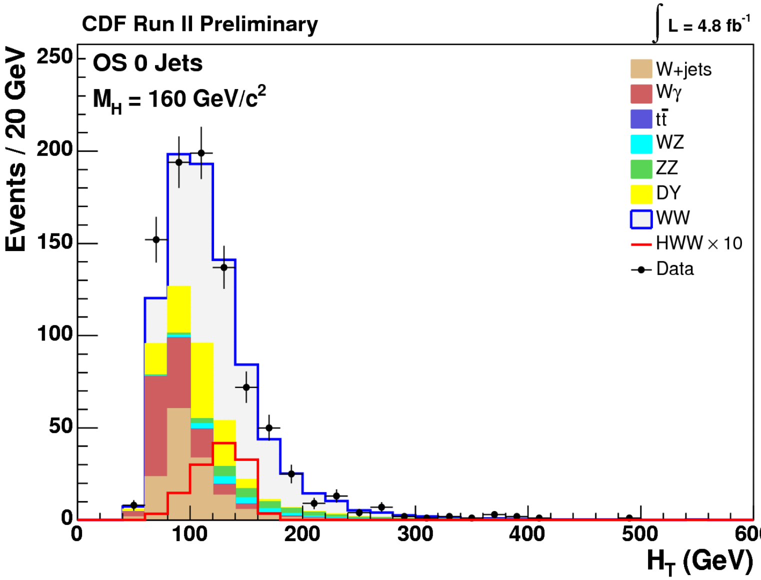
H → WW + 0 Jet Analysis

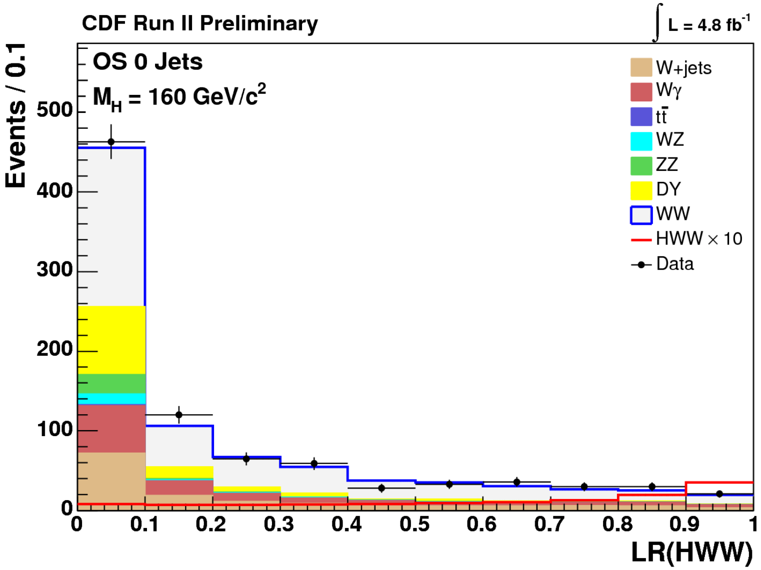
- Only consider gg → H production
  - ☐ Small contributions from VH and vector boson fusion



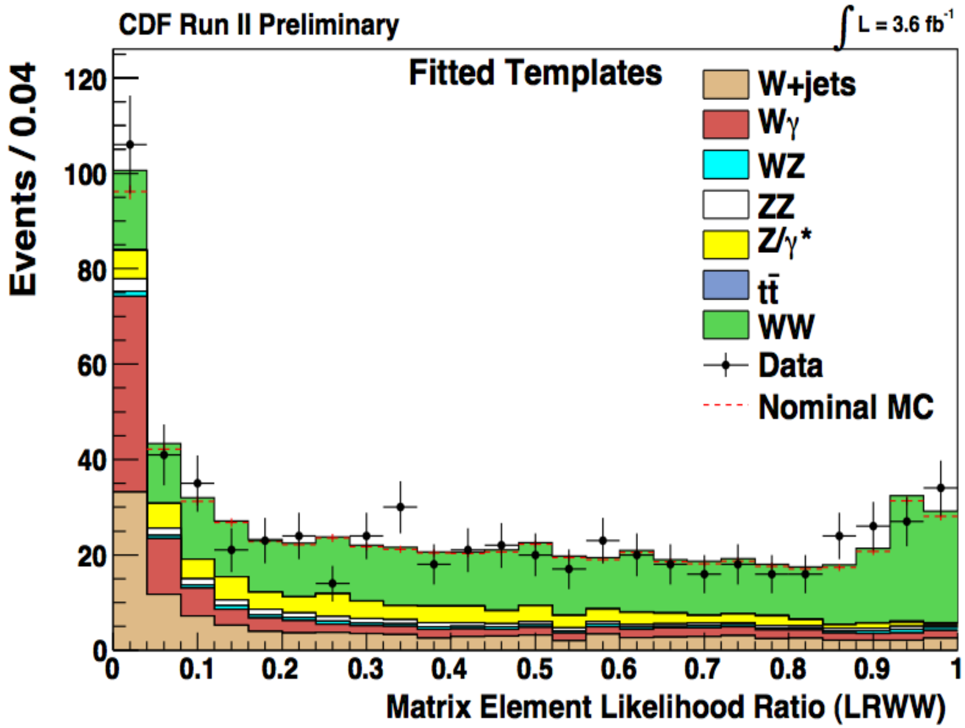
0 Jets	$m_H = 165$	Bkgd	Data
High S/B	10	516 ± 52	513
Low S/B	2	343 ± 40	372

- Dominant background WW
  - ☐ Dilepton opening angle best discriminant
- Inputs to Neural Network
  - ☐ Use kinematic variables and leading order matrix element-based likelihood ratios





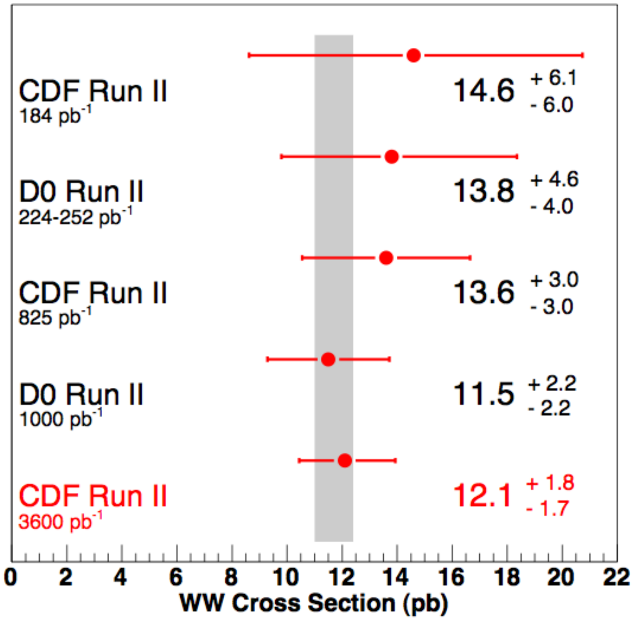
WW Cross Section



- Measure WW cross section in 0 jet signal region
- Maximum likelihood fit to WW likelihood ratio distribution
  - Systematic uncertainties included as Gaussian constraints in fit
- New world's best measurement!
  - Good agreement with theory (11.7 pb)

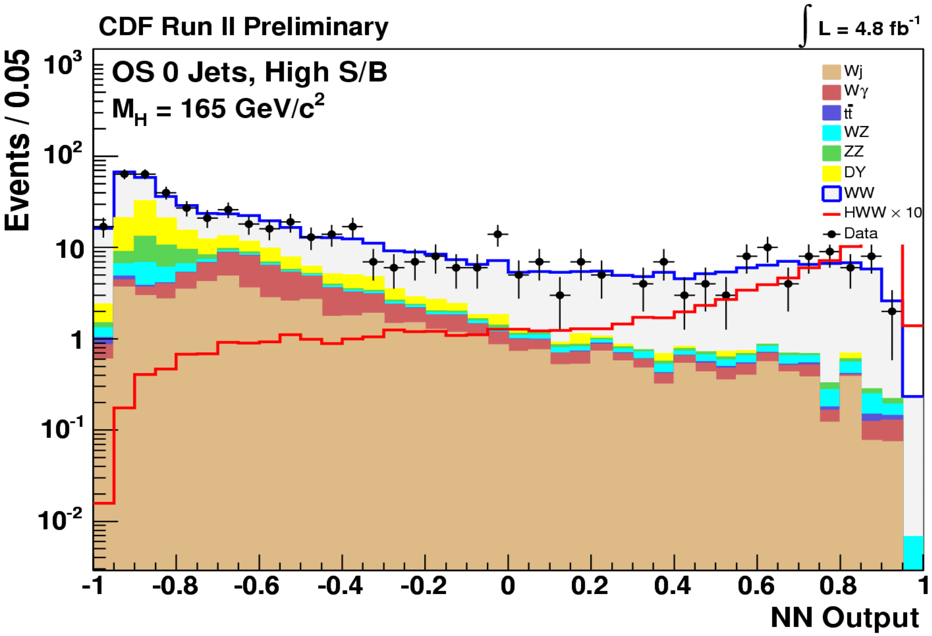
$$\sigma(p\bar{p} \rightarrow WW) = 12.1 \pm 0.9\ (\text{stat.})^{+1.6}_{-1.4}\ (\text{syst.})\ [\text{pb}]$$

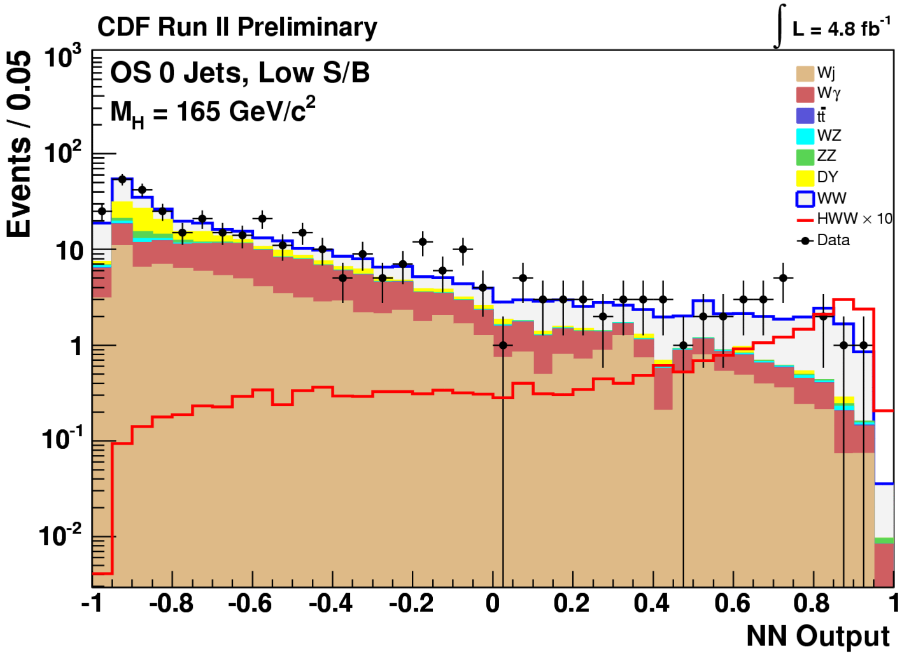
Syst. **includes** 5.9% luminosity uncertainty



H → WW + 0 Jet Results

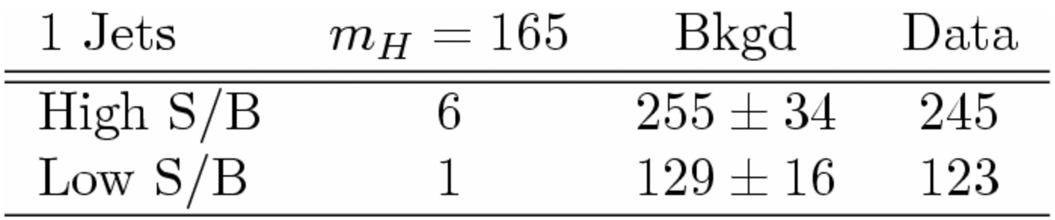
- Output of the Neural Network:
  - No excess observed at high NN score
  - Limits calculated from NN output distributions using Bayesian approach
- Majority of H→WW sensitivity comes from 0 jet channel





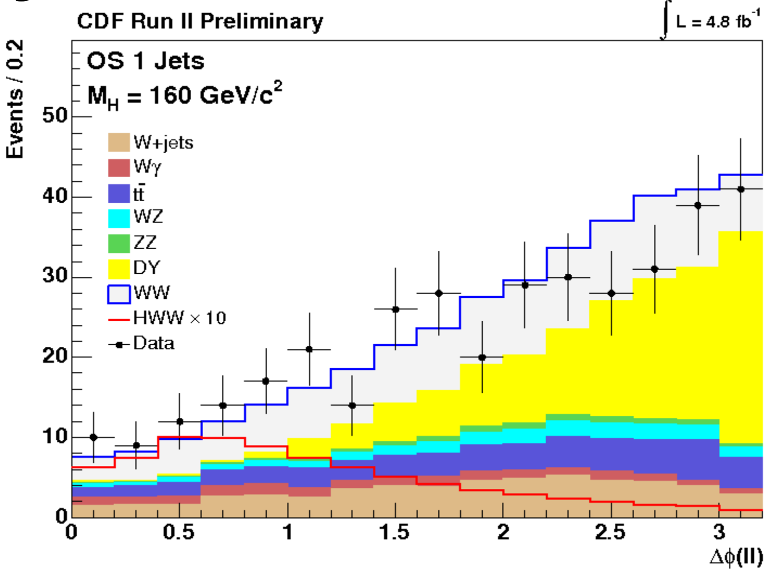
H → WW + 1 Jet Analysis

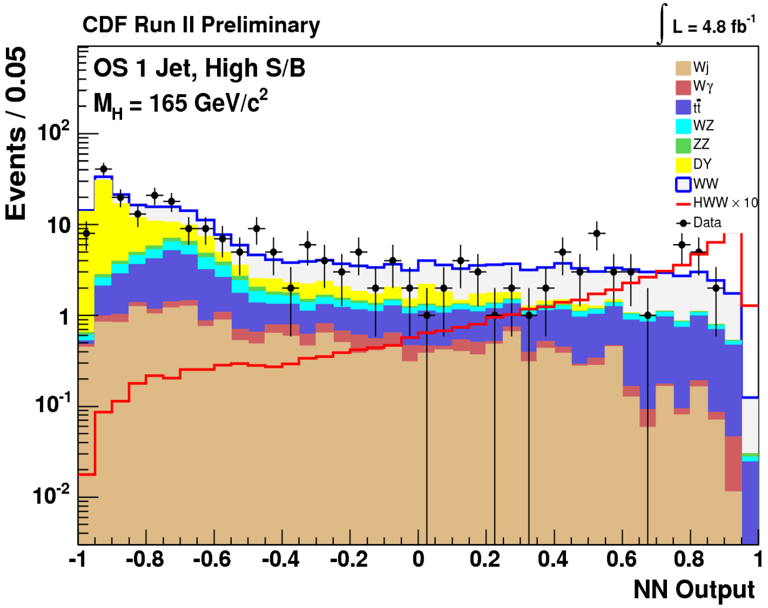
- Include VH and VBF signal
  - Additional 20% signal



1 Jets	$m_H = 165$	Bkgd	Data
High S/B	6	255 ± 34	245
Low S/B	1	129 ± 16	123

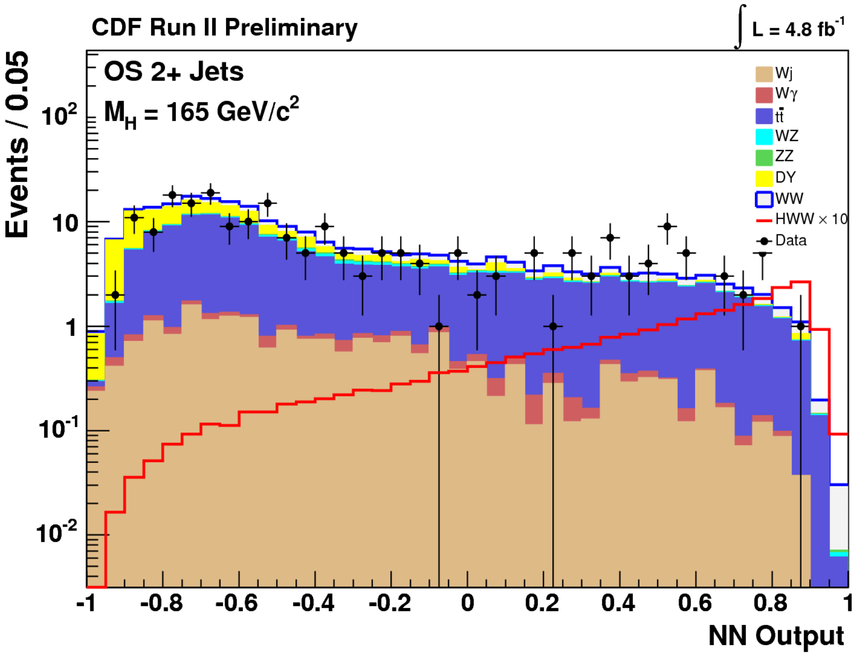
- Dominant background WW
  - Drell-Yan similar size
- Use kinematic input variables to Neural Networks
  - Matrix elements used only for 0 jet events



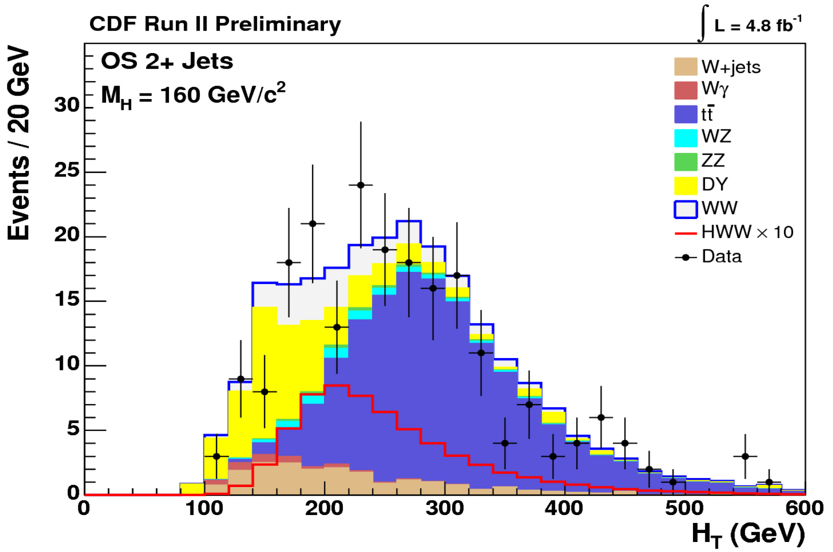


$H \rightarrow WW + \geq 2$ Jets Analysis

- No separation by lepton quality due to low statistics
- VH and VBF signal contributions dominant (60%)
- Largest background is $t\bar{t}$
  - Anti-*b*-tagging reduces $t\bar{t}$ background by > 50%
- Use kinematic input variables to Neural Networks

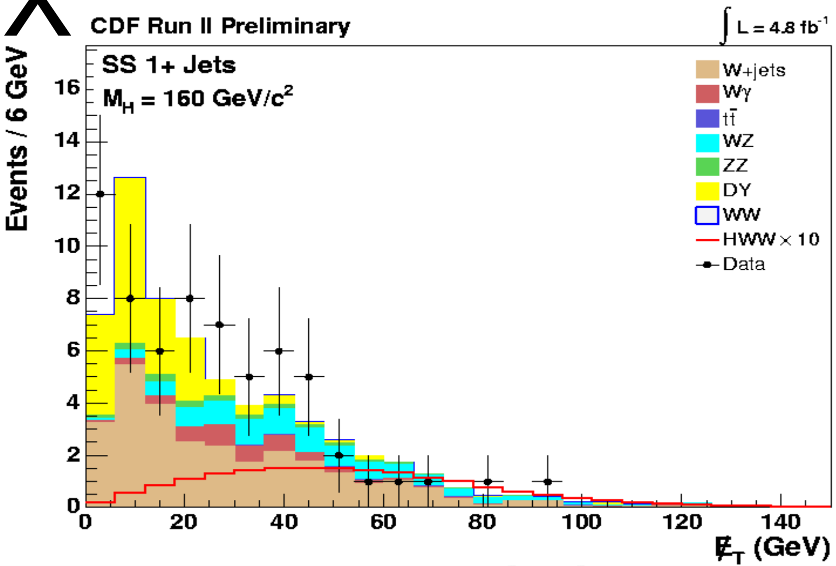


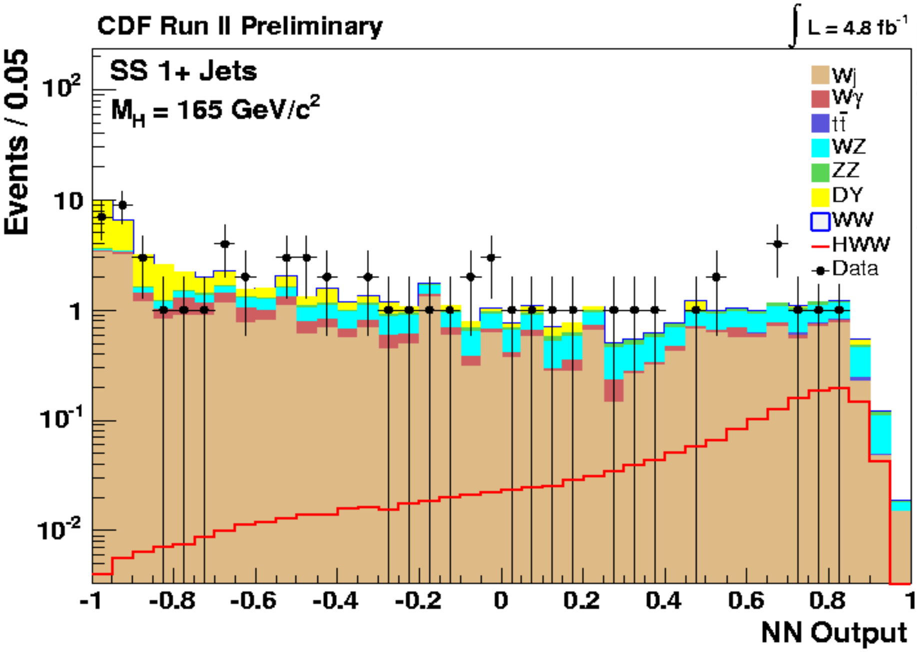
≥ 2 Jets	$m_H = 165$	Bkgd	Data
All S/B	6	237 ± 31	214



$VH \to VWW \to \ell\ell + X$

- $VH \to VWW \to \ell^{\pm}\ell^{\pm} + X$
  - Signature: like-sign dileptons
  - Background primarily from charge misidentification
  - Adds to high mass sensitivity





SS	$m_H = 165$	Bkgd	Data
0 Jets	~ 0	107 ± 19	98
1+ Jets	2	62 ± 11	64

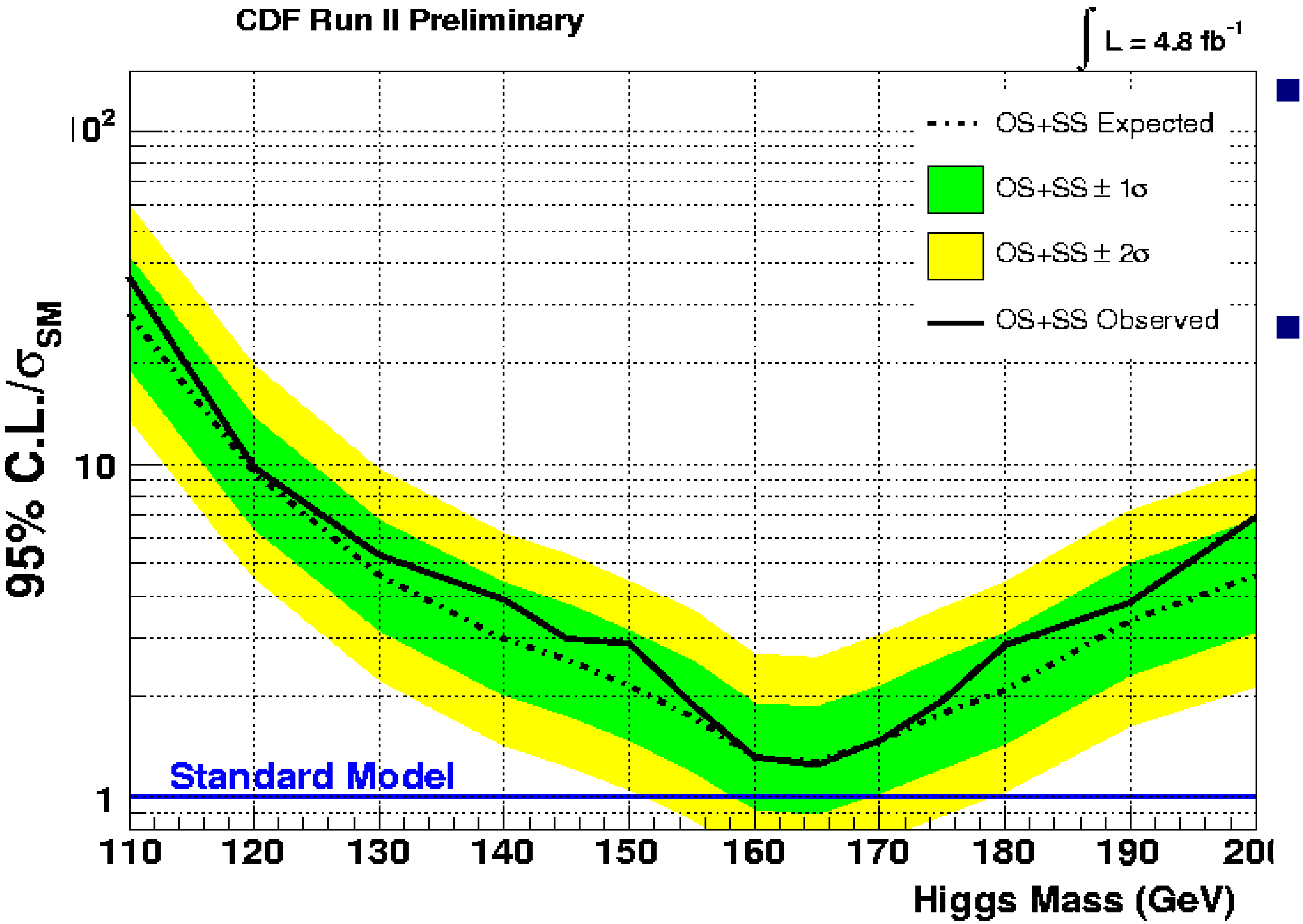
- Modified selection:
  - Do not use forward electrons, require ≥ 1 jets
  - Both leptons $p_T > 20$ GeV
  - No missing E_T cuts

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$ Systematics

Systematic (%)	Sig	Bkgs
Cross section	5-12	5-10
Conversions	0	20-30
NLO diagrams	3-10	5-10
PDF model	1-3	1-5
Jet modeling	1-2	1-30
Lepton ID	2	2
Trigger efficiency	2-3	2-7
Luminosity	6	6

- Two classes of systematics:
  - ☐ Shape
    - Modify output of discriminant
    - Studied but found to be negligible
  - ☐ Flat
    - Affect only normalization, do not modify shape
    - Dominant systematics

H → WW → $\ell\nu\ell\nu$ Limits



- Combine all high mass channels into one result
- At m_H = 165,
  - Observed (expected) limit of 1.25 (1.28)
  - Compare to 3.6 fb^{-1}: 1.33 (1.50) at m_H = 165

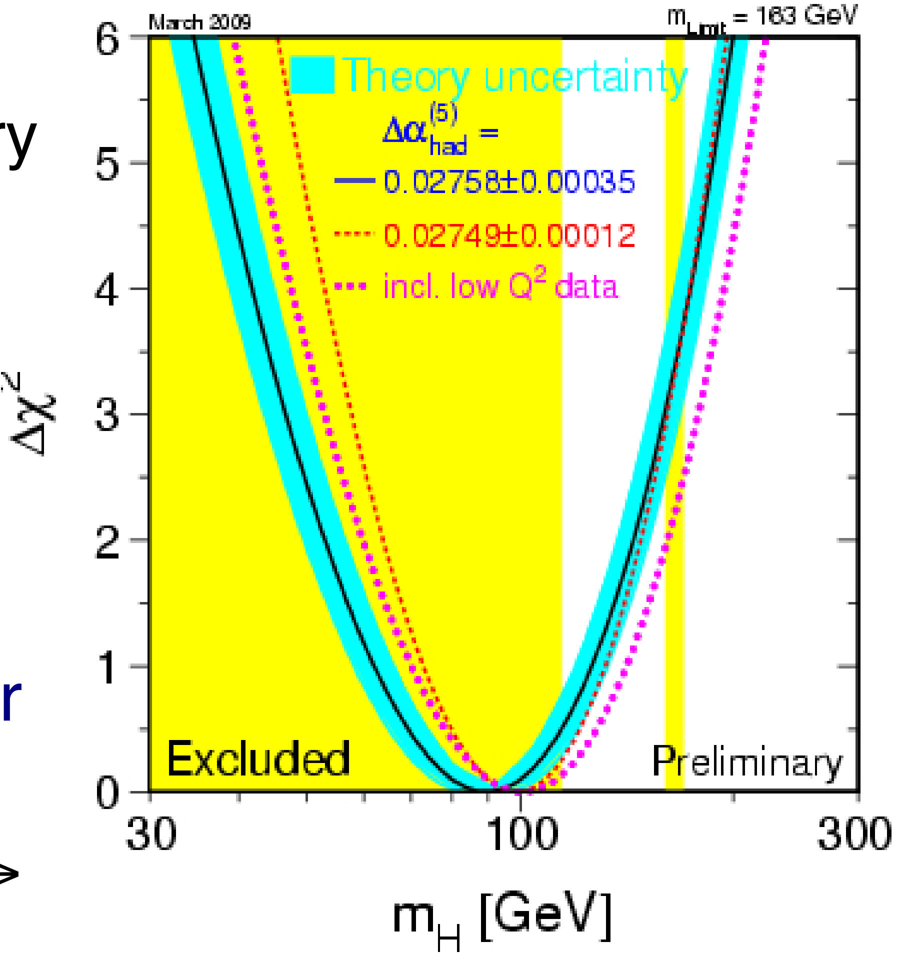
Summary

- Tevatron making great strides in SM Higgs searches
  - Rapid incorporation of new data and analysis improvements
    - March 2009: 3.6 fb^{-1}, July 2009: 4.8 fb^{-1}
    - Results available on http://www-cdf.fnal.gov/physics/new/hdg/results/hwwmenn_090710/
  - CDF and D0 both approaching Standard Model sensitivity at high masses
  - New Tevatron combination for Lepton-Photon Aug 2009
    - Incorporate new high and low mass results
- Tevatron excludes at 95% C.L. production of SM Higgs bosons in mass range 160-170 GeV
  - More to come...

Extra Slides

Standard Model and the Higgs

- Standard Model needs Higgs or Higgs-like mechanism to:
  - Explain electroweak symmetry breaking
  - Give particles mass
- Direct Higgs searches at LEP
  - Exclude Higgs of $M_H < 114.4$ GeV at 95% C.L.
- Indirect constraints from electroweak data prefer lighter Higgs ($M_H < 154$ GeV)
  - Combined with LEP results → upper limit of $M_H < 185$ GeV

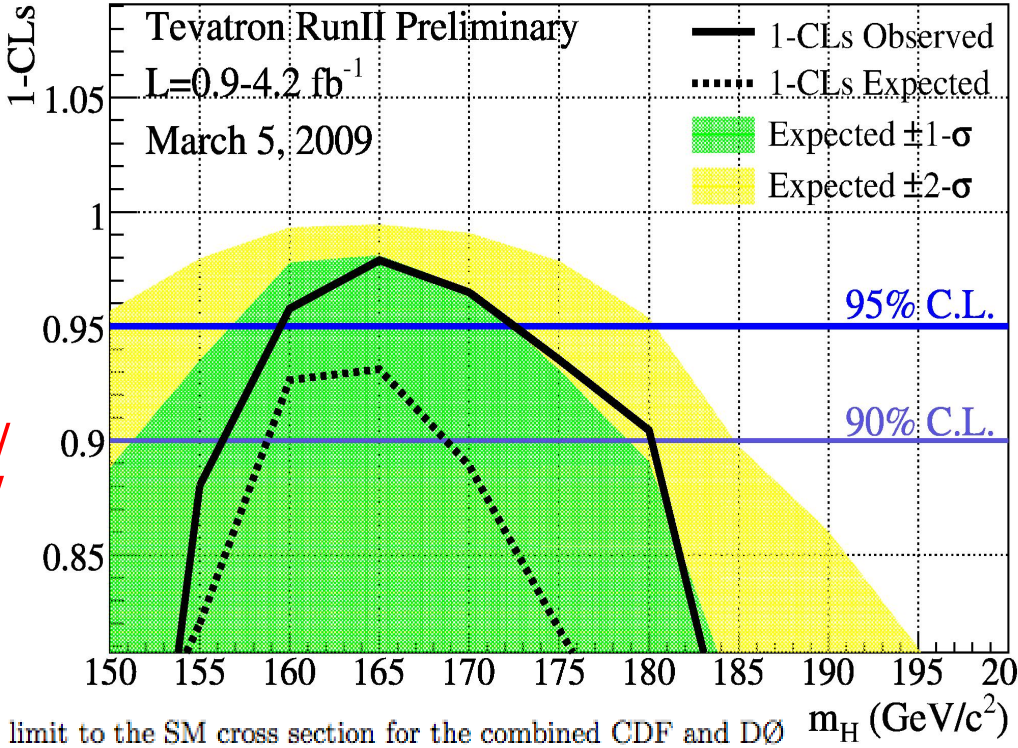


Plot from LEP EWK Working Group

Tevatron 3.6 fb^{-1} Combination

- Preliminary results first presented at Moriond 2009
- Available on public webpage:

  http://www-cdf.fnal.gov/physics/new/hdg/results/comb_090313/



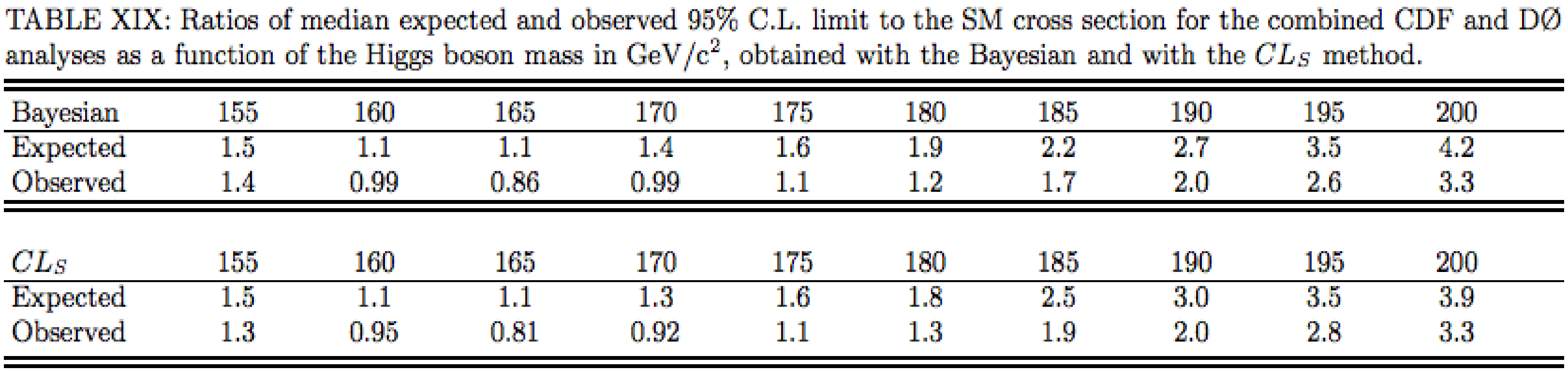
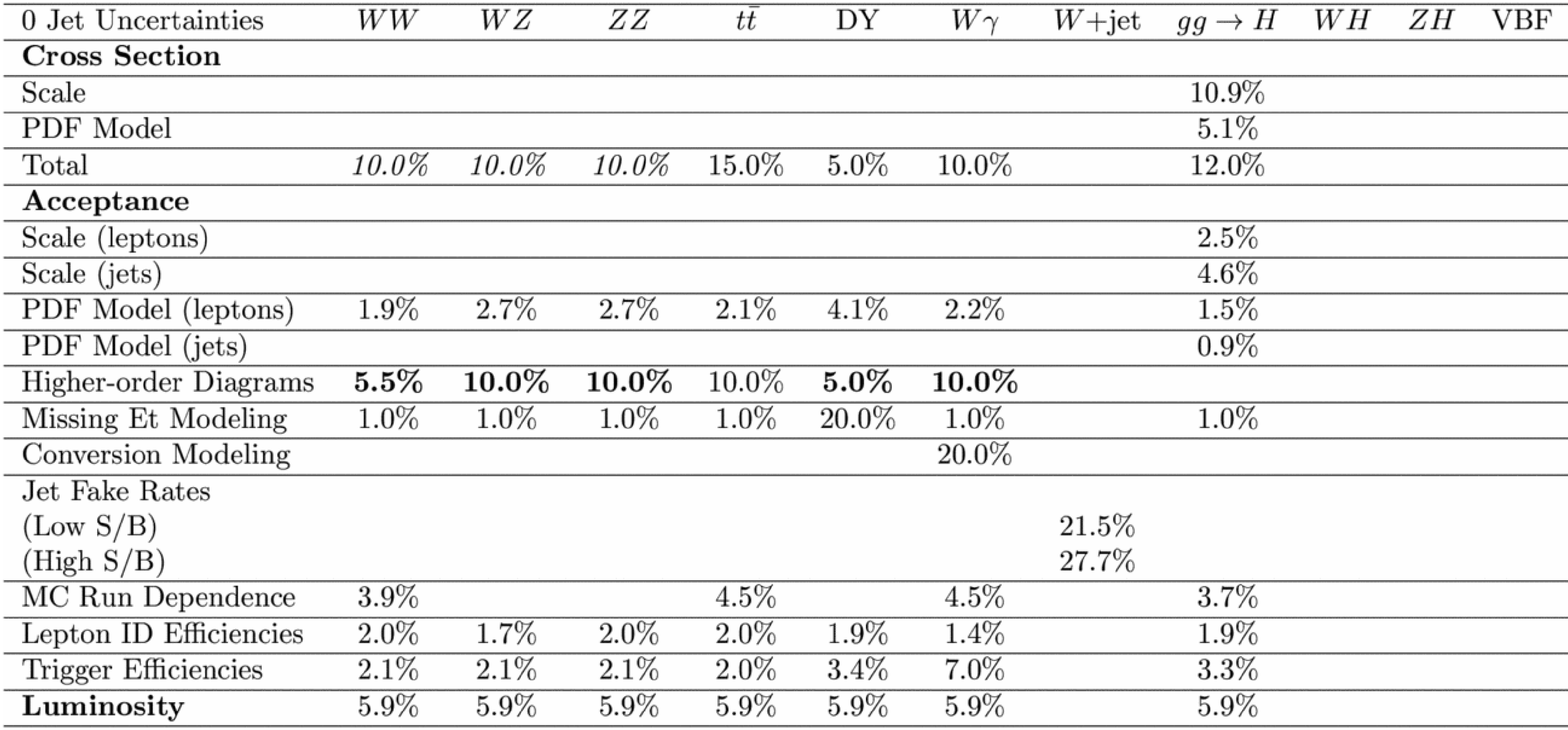


TABLE XIX: Ratios of median expected and observed 95% C.L. limit to the SM cross section for the combined CDF and DØ analyses as a function of the Higgs boson mass in GeV/c^2, obtained with the Bayesian and with the CL_S method.

Bayesian	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.4	1.6	1.9	2.2	2.7	3.5	4.2
Observed	1.4	0.99	0.86	0.99	1.1	1.2	1.7	2.0	2.6	3.3

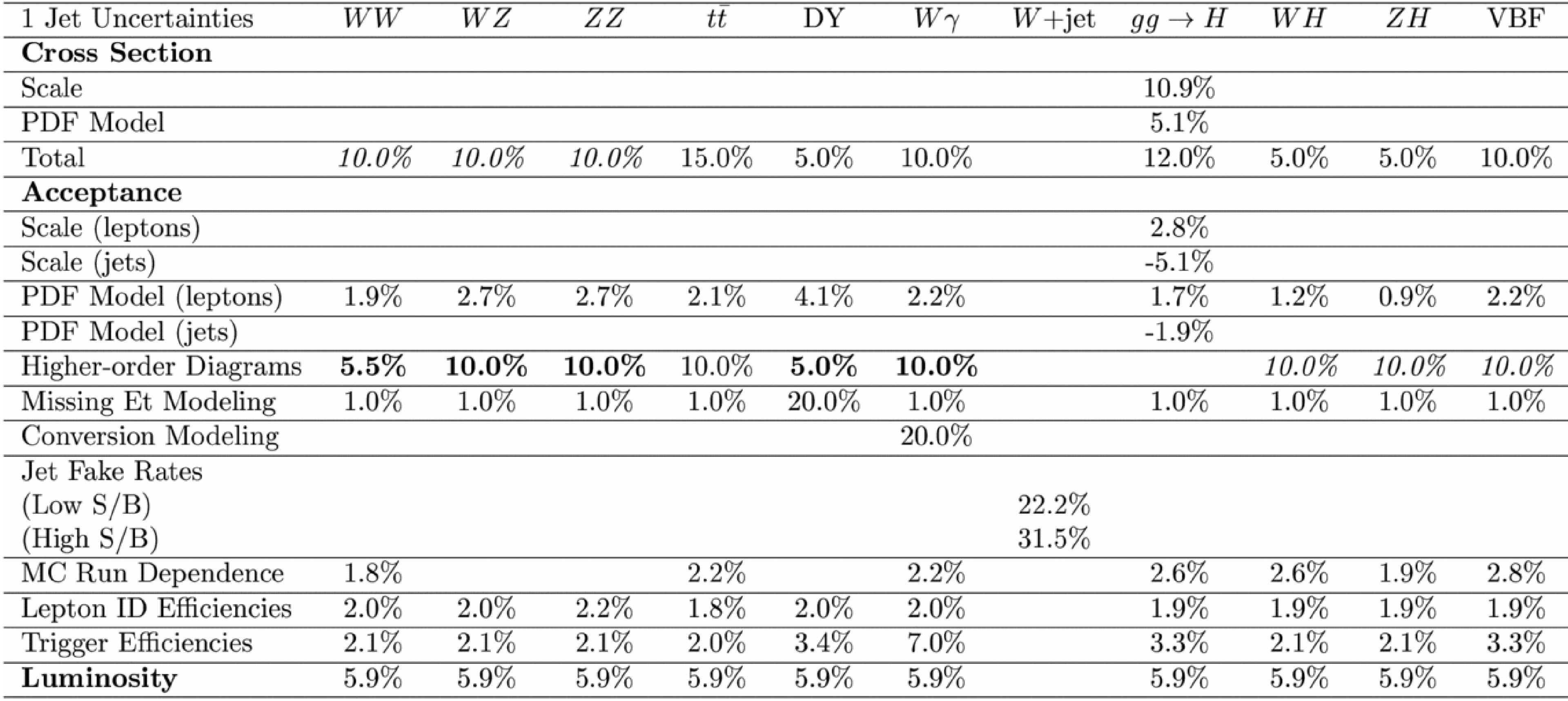
CL_S	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.3	1.6	1.8	2.5	3.0	3.5	3.9
Observed	1.3	0.95	0.81	0.92	1.1	1.3	1.9	2.0	2.8	3.3

H → WW 0 Jet Systematics



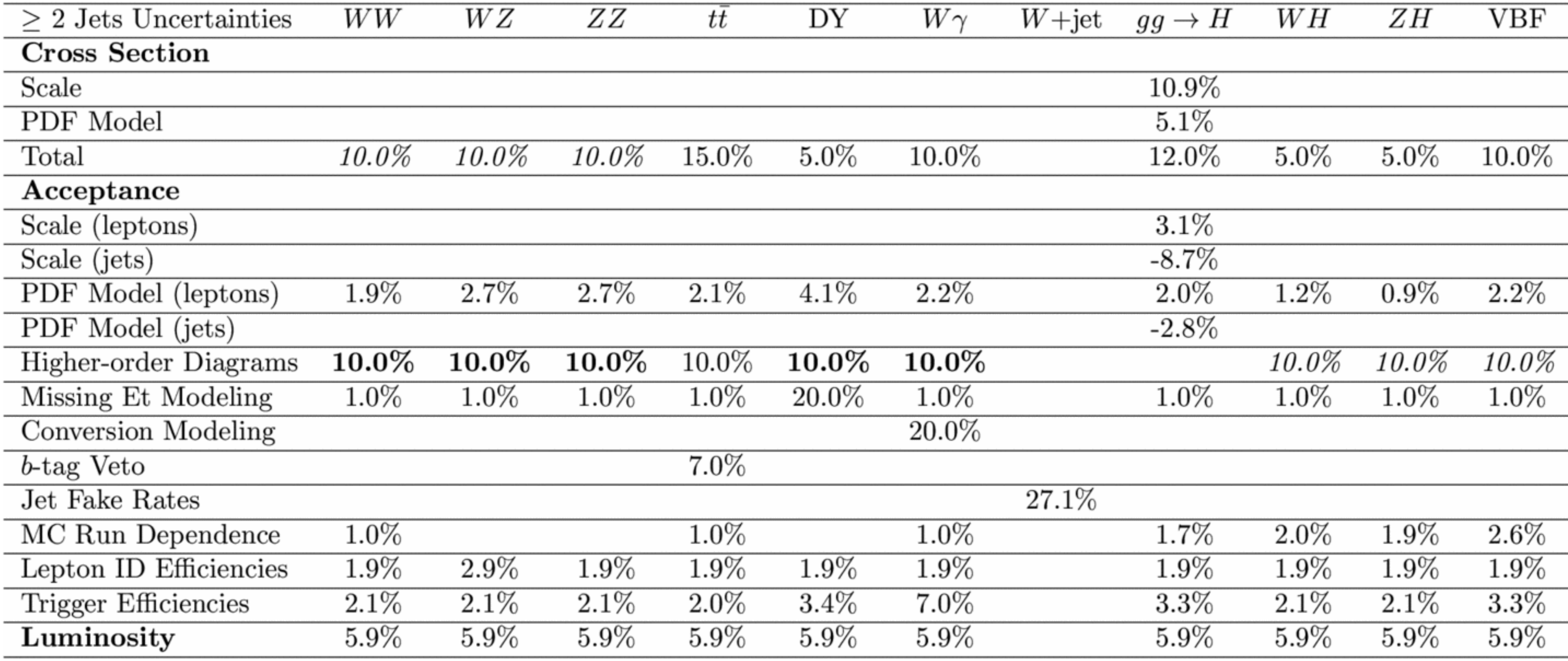
0 Jet Uncertainties	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								10.9%			
PDF Model								5.1%			
Total	*10.0%*	*10.0%*	*10.0%*	15.0%	5.0%	10.0%		12.0%			
Acceptance											
Scale (leptons)								2.5%			
Scale (jets)								4.6%			
PDF Model (leptons)	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%		1.5%			
PDF Model (jets)								0.9%			
Higher-order Diagrams	**5.5%**	**10.0%**	**10.0%**	10.0%	**5.0%**	**10.0%**					
Missing Et Modeling	1.0%	1.0%	1.0%	1.0%	20.0%	1.0%		1.0%			
Conversion Modeling						20.0%					
Jet Fake Rates											
(Low S/B)							21.5%				
(High S/B)							27.7%				
MC Run Dependence	3.9%			4.5%		4.5%		3.7%			
Lepton ID Efficiencies	2.0%	1.7%	2.0%	2.0%	1.9%	1.4%		1.9%			
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%	7.0%		3.3%			
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%	5.9%		5.9%			

H → WW 1 Jet Systematics



1 Jet Uncertainties	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								10.9%			
PDF Model								5.1%			
Total	*10.0%*	*10.0%*	*10.0%*	15.0%	5.0%	10.0%		12.0%	5.0%	5.0%	10.0%
Acceptance											
Scale (leptons)								2.8%			
Scale (jets)								-5.1%			
PDF Model (leptons)	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%		1.7%	1.2%	0.9%	2.2%
PDF Model (jets)								-1.9%			
Higher-order Diagrams	**5.5%**	**10.0%**	**10.0%**	10.0%	**5.0%**	**10.0%**			*10.0%*	*10.0%*	*10.0%*
Missing Et Modeling	1.0%	1.0%	1.0%	1.0%	20.0%	1.0%		1.0%	1.0%	1.0%	1.0%
Conversion Modeling						20.0%					
Jet Fake Rates											
(Low S/B)							22.2%				
(High S/B)							31.5%				
MC Run Dependence	1.8%			2.2%		2.2%		2.6%	2.6%	1.9%	2.8%
Lepton ID Efficiencies	2.0%	2.0%	2.2%	1.8%	2.0%	2.0%		1.9%	1.9%	1.9%	1.9%
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%	7.0%		3.3%	2.1%	2.1%	3.3%
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%	5.9%		5.9%	5.9%	5.9%	5.9%

H → WW ≥ 2 Jets Systematics



$\geq$ 2 Jets Uncertainties	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								10.9%			
PDF Model								5.1%			
Total	*10.0%*	*10.0%*	*10.0%*	15.0%	5.0%	10.0%		12.0%	5.0%	5.0%	10.0%
Acceptance											
Scale (leptons)								3.1%			
Scale (jets)								-8.7%			
PDF Model (leptons)	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%		2.0%	1.2%	0.9%	2.2%
PDF Model (jets)								-2.8%			
Higher-order Diagrams	**10.0%**	**10.0%**	**10.0%**	10.0%	**10.0%**	**10.0%**			*10.0%*	*10.0%*	*10.0%*
Missing Et Modeling	1.0%	1.0%	1.0%	1.0%	20.0%	1.0%		1.0%	1.0%	1.0%	1.0%
Conversion Modeling						20.0%					
b-tag Veto				7.0%							
Jet Fake Rates							27.1%				
MC Run Dependence	1.0%			1.0%		1.0%		1.7%	2.0%	1.9%	2.6%
Lepton ID Efficiencies	1.9%	2.9%	1.9%	1.9%	1.9%	1.9%		1.9%	1.9%	1.9%	1.9%
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%	7.0%		3.3%	2.1%	2.1%	3.3%
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%	5.9%		5.9%	5.9%	5.9%	5.9%

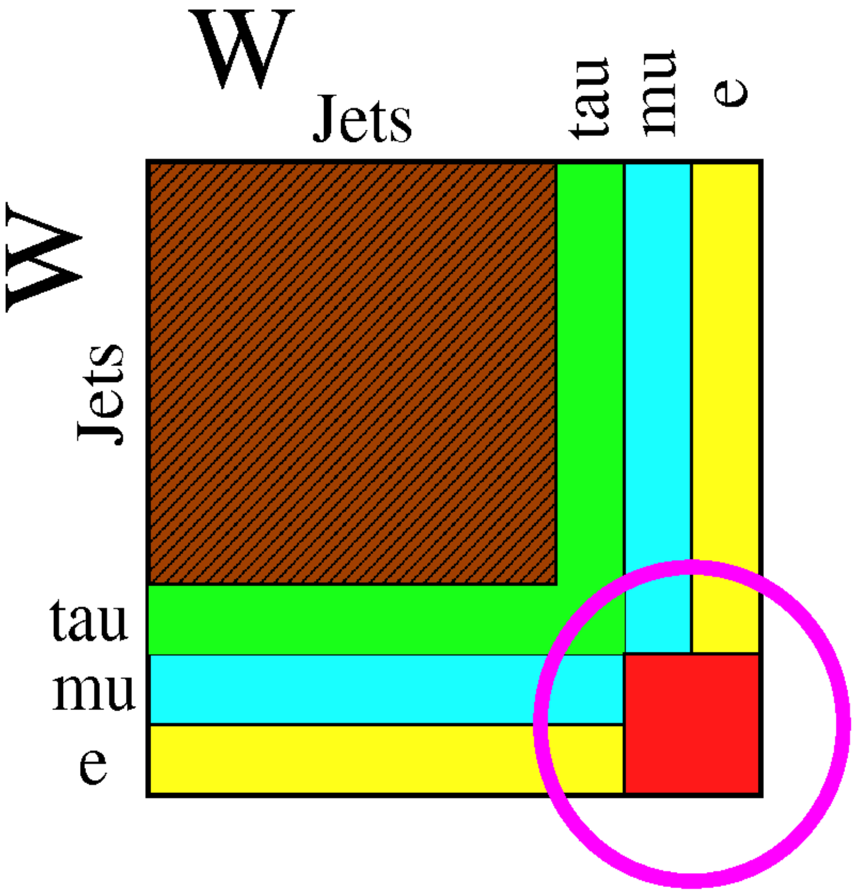
H → WW ≥ 1 Jets SS Systematics

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet
Cross Section							
Scale							
PDF Model							
Total	6.0%	6.0%	6.0%	10.0%	5.0%	10.0%	
Acceptance							
Scale							
PDF Model	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%	
Higher-order Diagrams	5.0%	10.0%	10.0%	10.0%		10.0%	
Jet Modeling	3.0%				17.0%	16.0%	
Conversion Modeling						20.0%	
Charge Mismeasurement Rate	16.5%			16.5%	16.5%		
Jet Fake Rates							30.0%
MC Run Dependence	1.9%			1.0%			
Lepton ID Efficiencies	2.0%	2.0%	2.0%	2.0%	2.0%		
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%		
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%		

Uncertainty Source	$gg \to H$	WH	ZH
Cross Section			
Scale			
PDF Model			
Total		5.0%	5.0%
Acceptance			
PDF Model (leptons)		1.2%	0.9%
EWK Higher-order Diagrams		10.0%	10.0%
Lepton ID Efficiencies		2.0%	2.0%
Trigger Efficiencies		2.1%	2.1%
Luminosity		5.9%	5.9%

H → W^+W^- Final States

- W decay modes
  - ☐ Leptonic 33% (e, μ)
  - ☐ Hadronic 67%
- Dilepton (e, μ): BR ~ 6%
  - ☐ Sensitive to τ → (e, μ)
  - ☐ Small BR, but…
    clean, easy to trigger
- Lepton + τ_{had}: BR ~ 4%
  - ☐ Potentially useful
- Lepton + jets: BR ~ 30%
  - ☐ Large W+jets background
- All hadronic: BR ~ 45%
  - ☐ Large QCD background



Matrix Elements

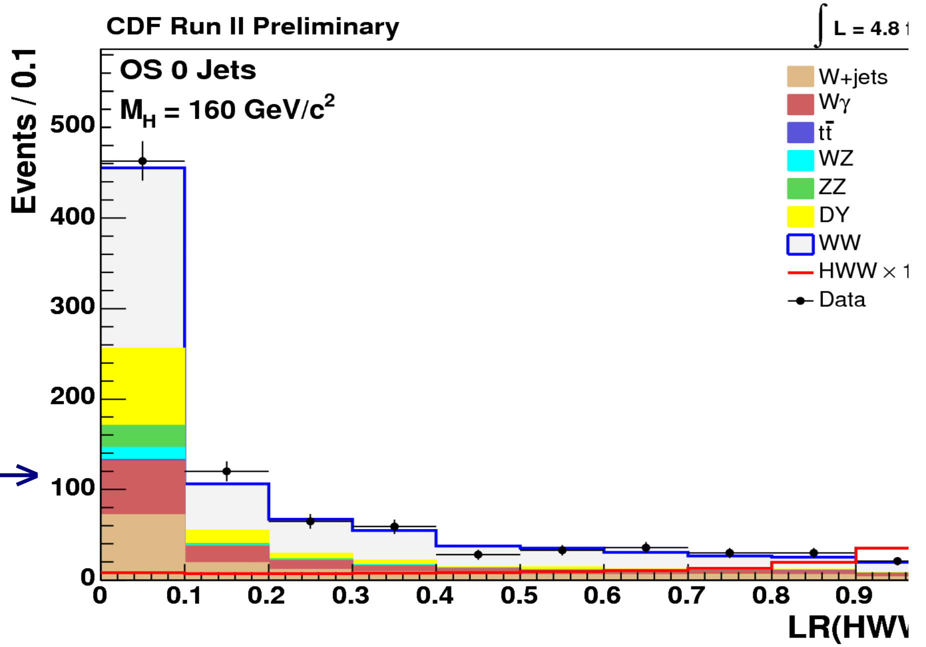
$$P(\vec{x}_{obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \, \varepsilon(\vec{y}) \, G(\vec{x}_{obs}, \vec{y}) \, d\vec{y}$$

- Event-by-event probability density

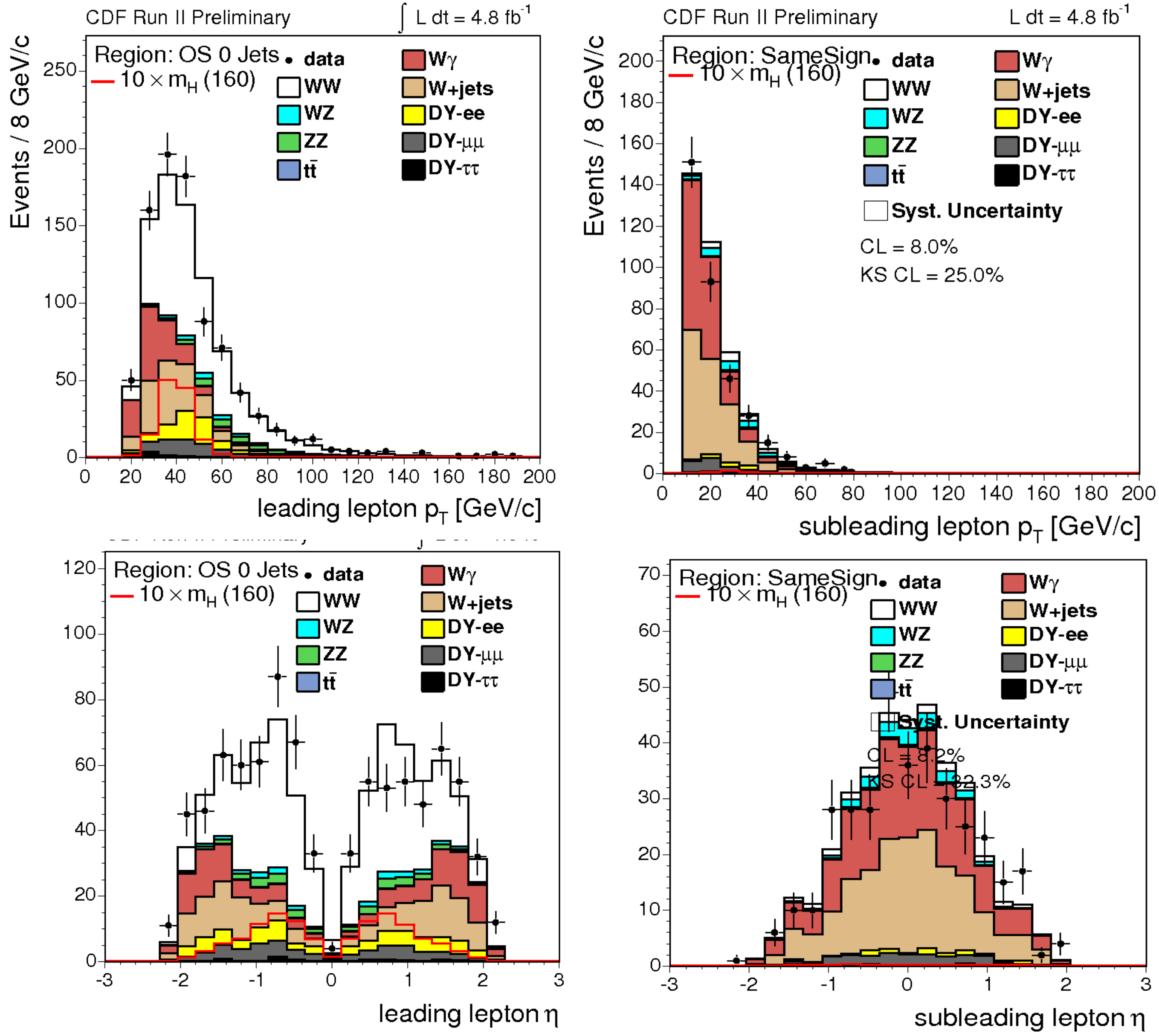
$\vec{x}_{obs}$	Observed leptons and $\not{E}_T$
$\vec{y}$	True lepton 4-vectors (l, ν)
σ_{th}	Leading order theoretical cross-section
$\varepsilon(\vec{y})$	Efficiency & acceptance
$G(\vec{x}_{obs}, \vec{y})$	Resolution effects
$1/\langle\sigma\rangle$	Normalization

$$LR_m = \frac{P_m(\vec{x}_{obs})}{P_m(\vec{x}_{obs}) + \sum_i k_i P_i(\vec{x}_{obs})}$$

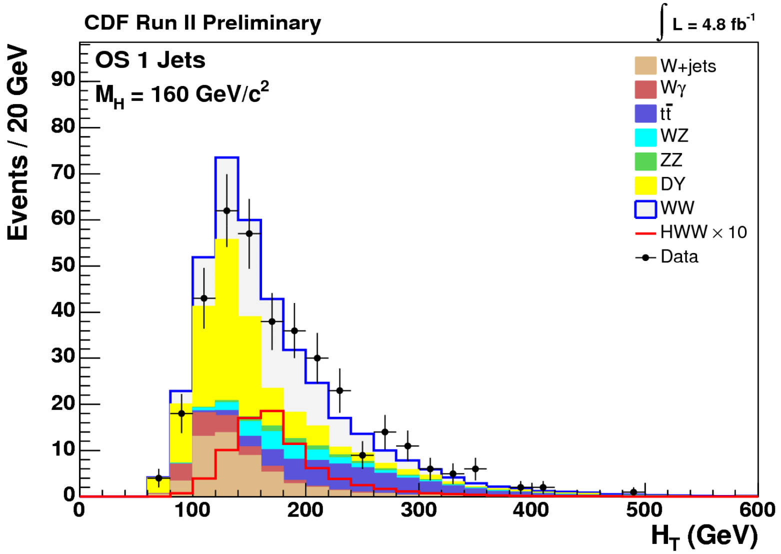
- Model 5 modes:
  - HWW, WW, ZZ, Wγ, W+jet
- Construct Likelihood Ratio →

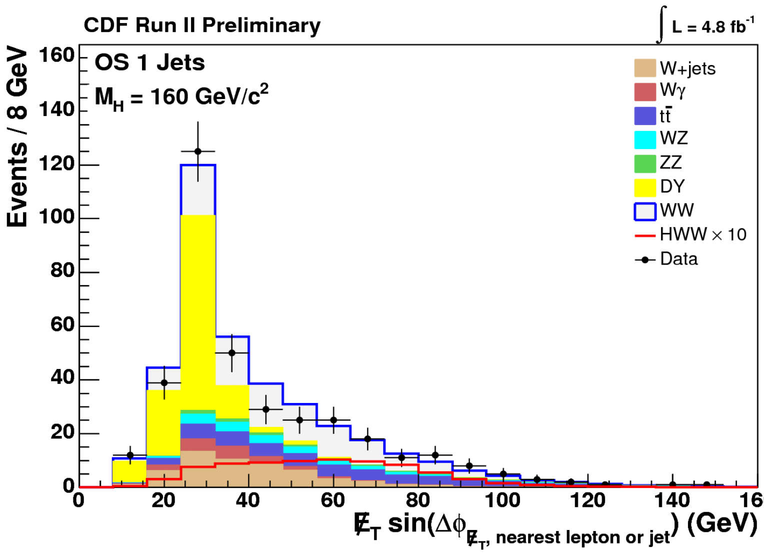


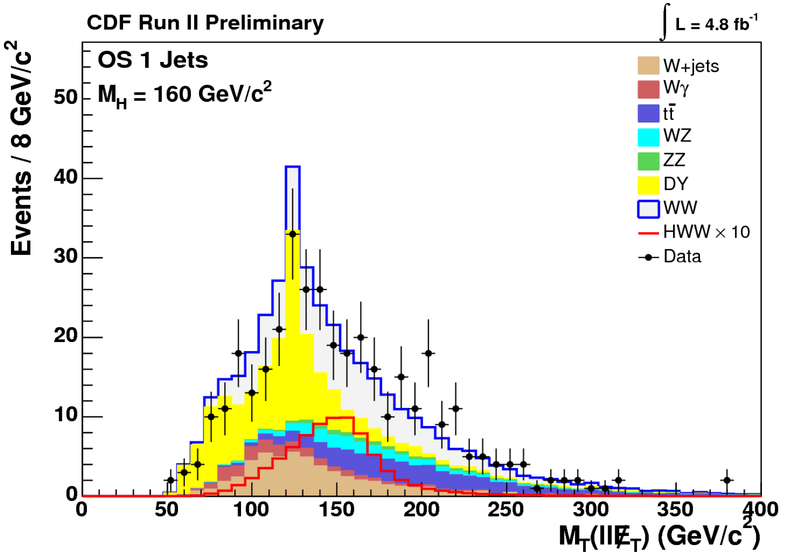
0 Jet Kinematic Plots

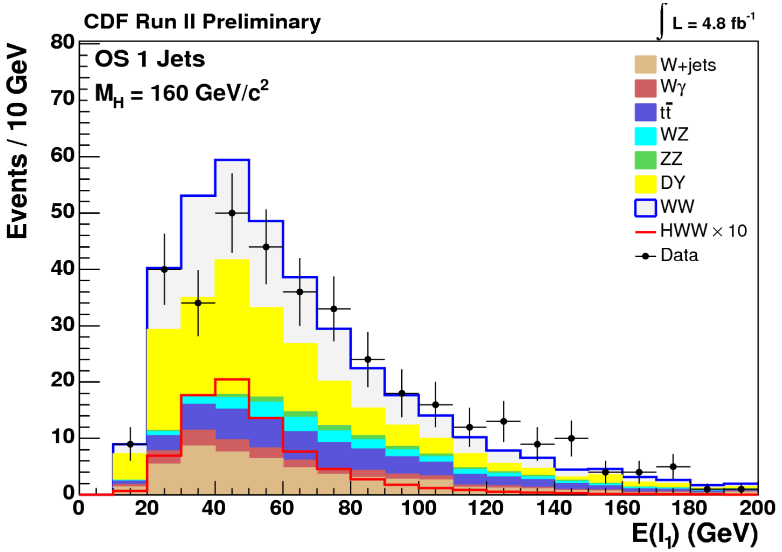


1 Jet NN Inputs

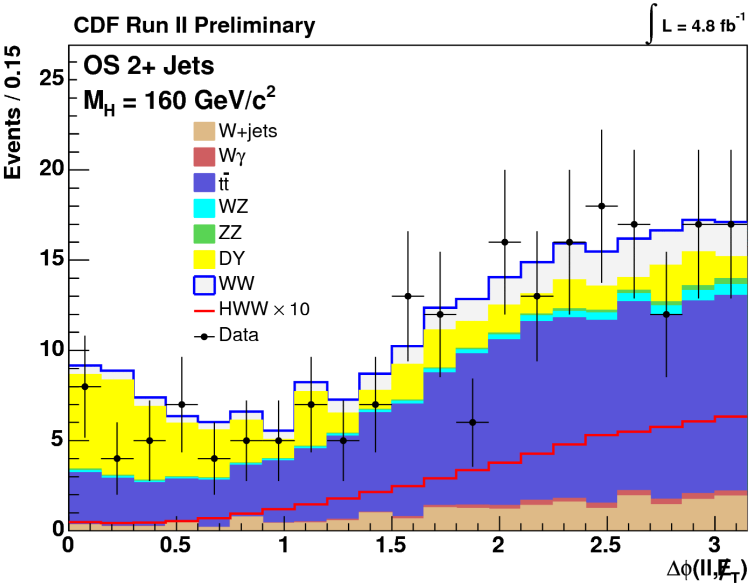


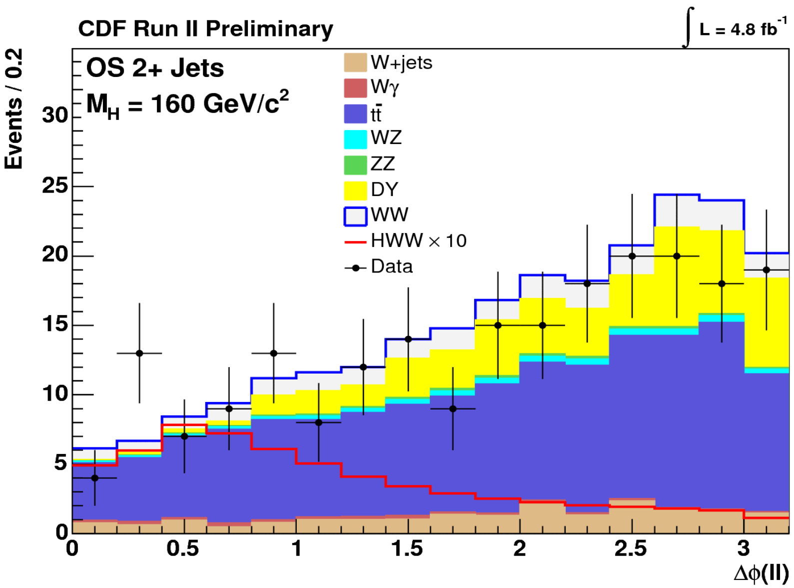


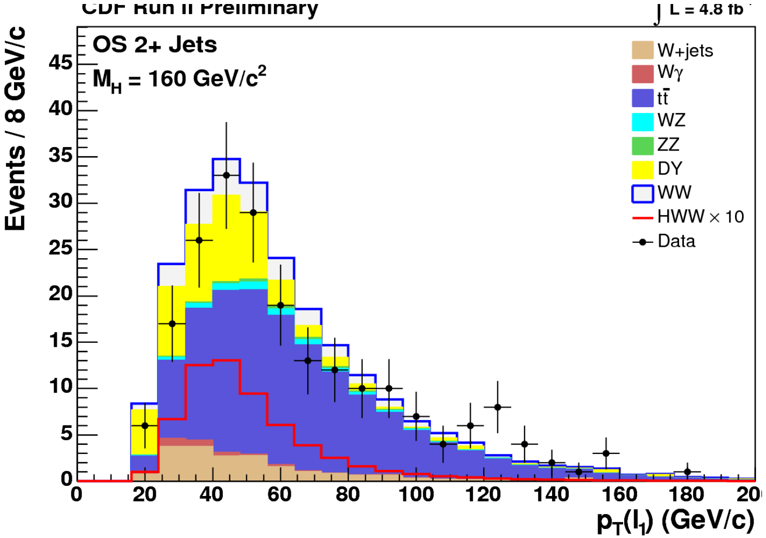


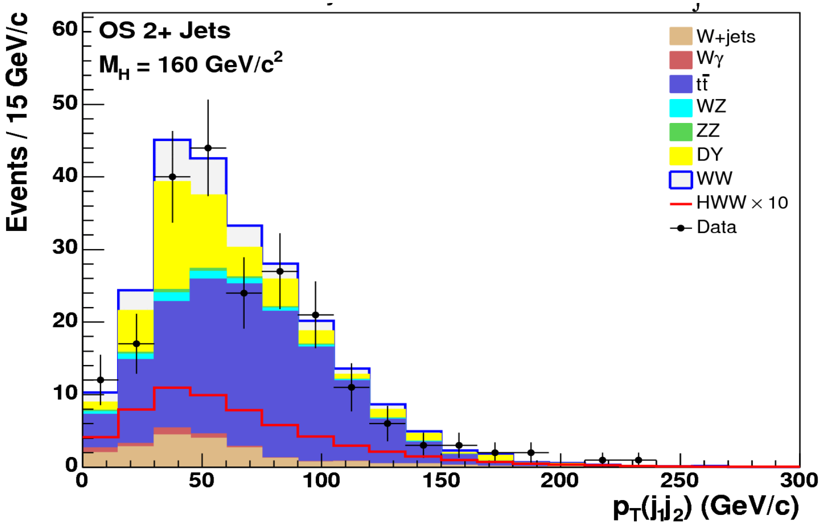


2+ Jet NN Inputs

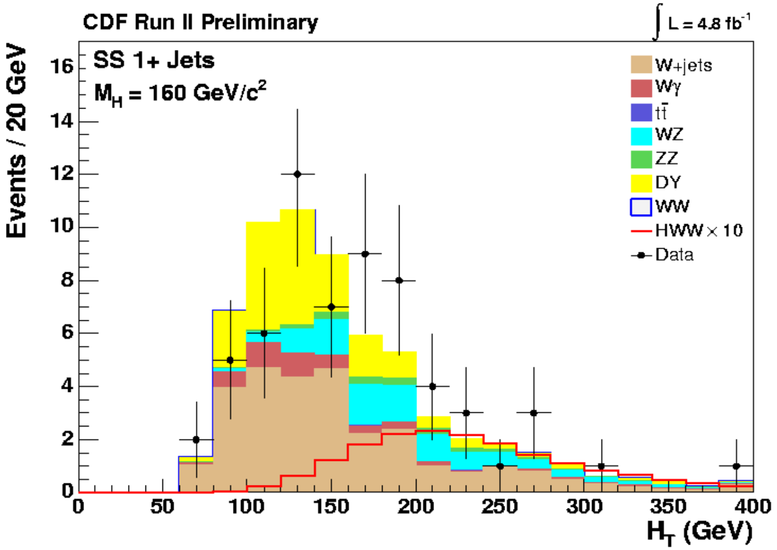


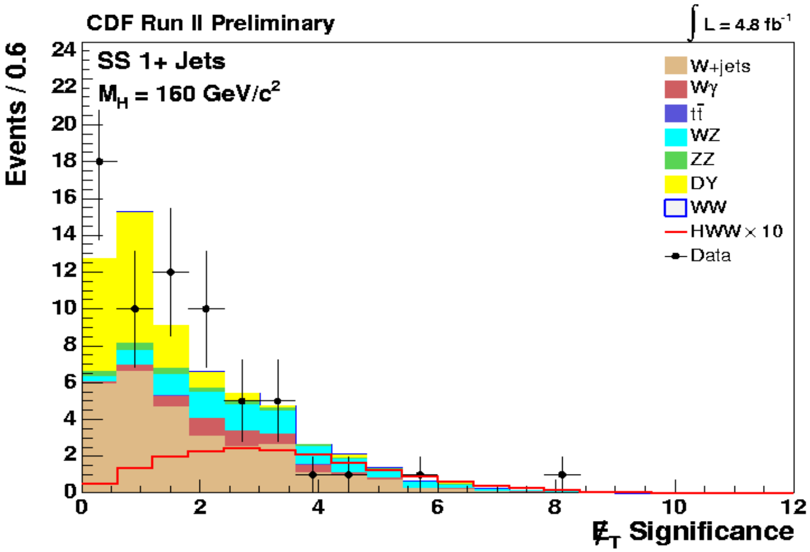


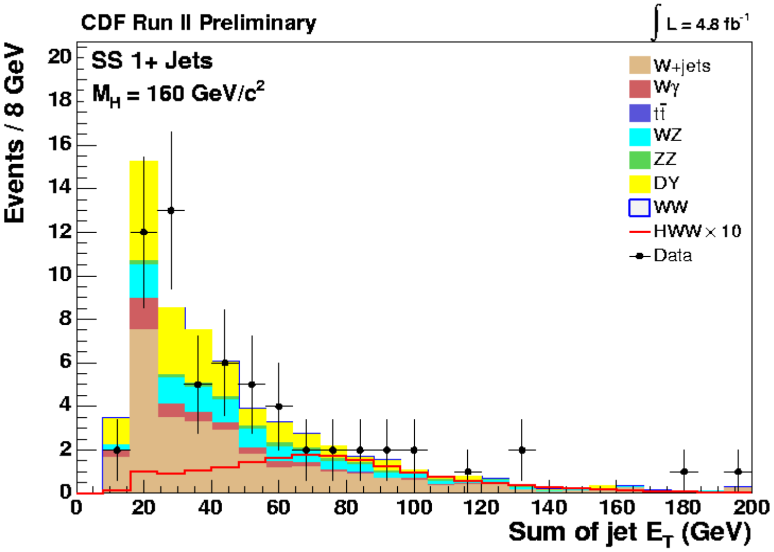


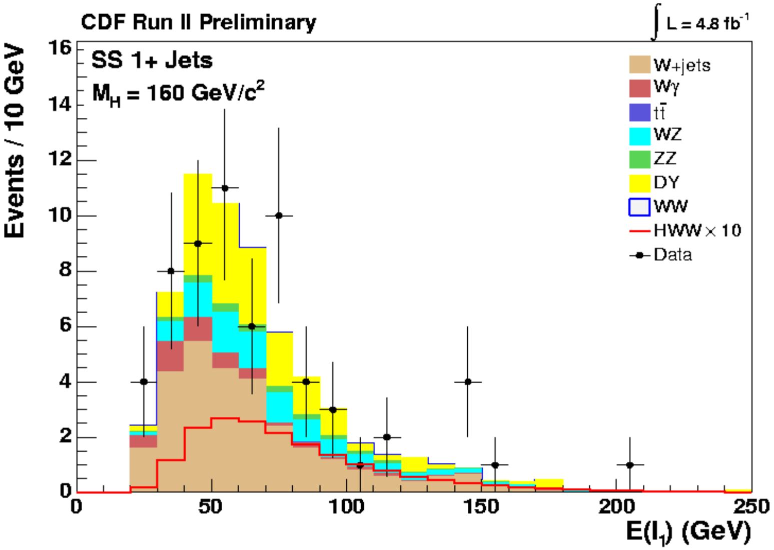


SS NN Inputs

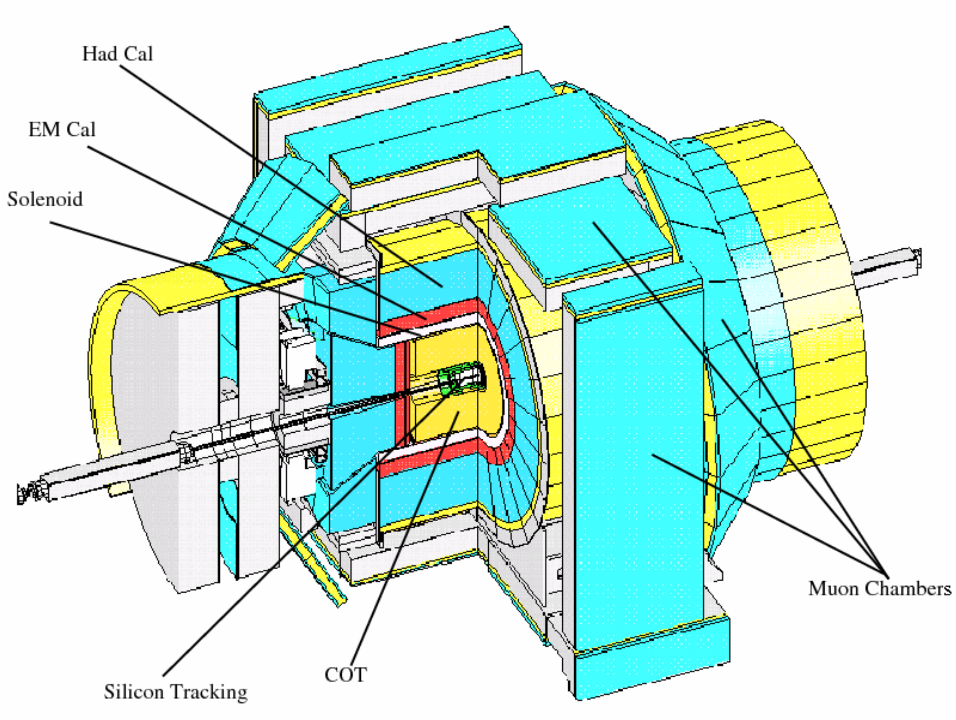

CDF Run II Preliminary
∫ L = 4.8 fb⁻¹
SS 1+ Jets
M_H = 160 GeV/c²
W+jets
Wγ
tt̄
WZ
ZZ
DY
WW
HWW × 10
Data
Events / 20 GeV
0
2
4
6
8
10
12
14
16
0
50
100
150
200
250
300
350
400
H_T (GeV)

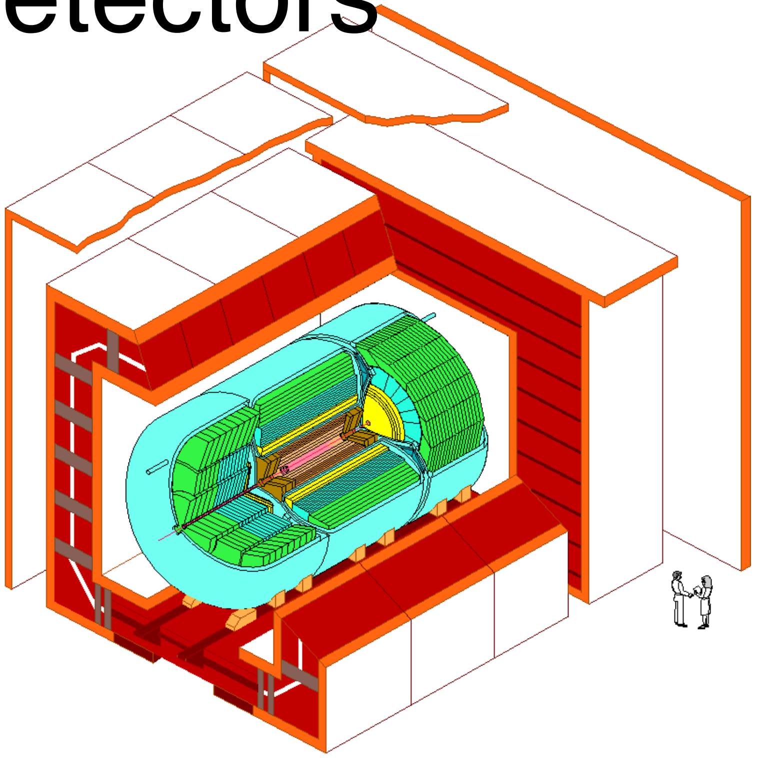

CDF Run II Preliminary
∫ L = 4.8 fb⁻¹
SS 1+ Jets
M_H = 160 GeV/c²
W+jets
Wγ
tt̄
WZ
ZZ
DY
WW
HWW × 10
Data
Events / 0.6
0
2
4
6
8
10
12
14
16
18
20
22
24
0
2
4
6
8
10
12
E̸_T Significance


CDF Run II Preliminary
∫ L = 4.8 fb⁻¹
SS 1+ Jets
M_H = 160 GeV/c²
W+jets
Wγ
tt̄
WZ
ZZ
DY
WW
HWW × 10
Data
Events / 8 GeV
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
160
180
200
Sum of jet E_T (GeV)


CDF Run II Preliminary
∫ L = 4.8 fb⁻¹
SS 1+ Jets
M_H = 160 GeV/c²
W+jets
Wγ
tt̄
WZ
ZZ
DY
WW
HWW × 10
Data
Events / 10 GeV
0
2
4
6
8
10
12
14
16
0
50
100
150
200
250
E(l_1) (GeV)

CDF and D0 Detectors





DØ Detector

- CDF
  - ☐ Silicon inner tracker, wire drift chamber outer
  - ☐ EM and had calorimeters
  - ☐ Muon coverage $|\eta|< 1.5$
- D0
  - ☐ Silicon inner tracker, fiber outer tracker
  - ☐ LAr-U calorimeter
  - ☐ Good muon coverage