The Tevatron's Search for High Mass Higgs Bosons

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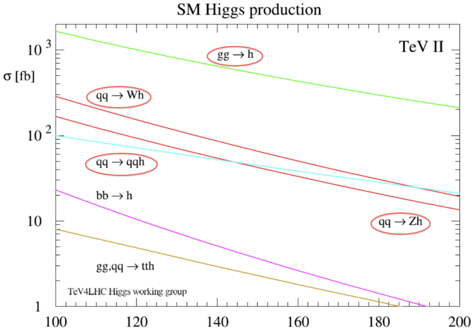
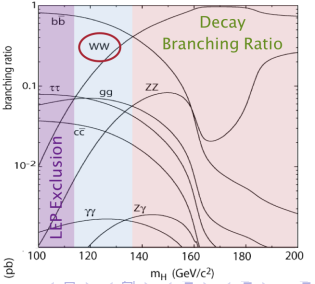
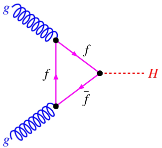
On behalf of the CDF and DØ Collaborations

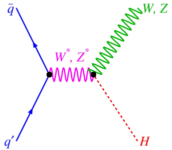
High mass Higgs searches at the Tevatron

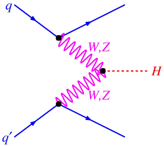
- Higgs production cross sections for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
  - Gluon fusion $\sigma \approx 0.2 - 1$ pb
  - Associated production $\sigma \approx 0.01 - 0.3$ pb
  - Vector Boson Fusion $\sigma \approx 0.01 - 0.1$ pb
- Precision ewk data + searches (excl. LHC) yield $M_H \in (114, 185)$ GeV @95 C.L
- High Mass: Searches optimised for $M_H \geq 135$ GeV
  - Main Decay mode is WW



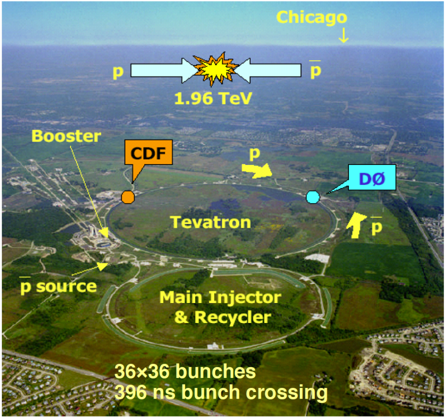


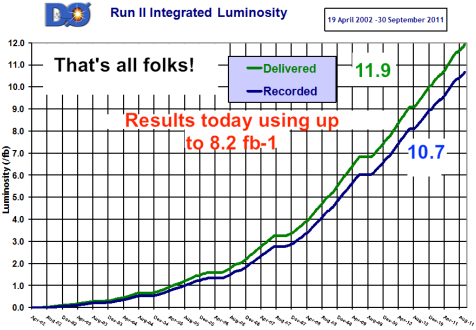






The Tevatron

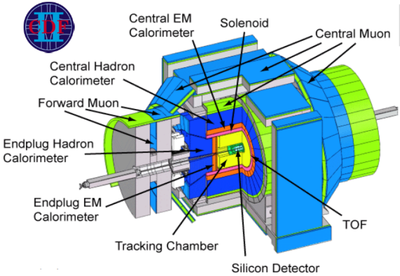


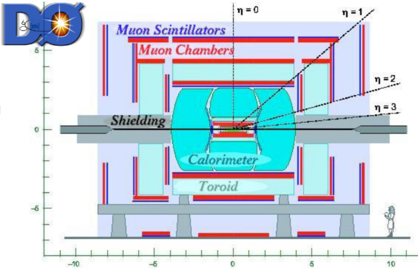


- RunI 1993-1996 $\sim 120\,\mathrm{pb}^{-1}$ per exp.
- RunII 2002-September 2011 $\sim 12(11)\,\mathrm{fb}^{-1}$ del. (rec.) per exp.
- $\sim 10\,\mathrm{fb}^{-1}$ available for physics analyses
- **Presenting: D0 up to $8.1\,\mathrm{fb}^{-1}$, CDF up to $8.2\,\mathrm{fb}^{-1}$**

CDF and DØ detectors

General purpose hermetic detectors





	CDF		D0	
Tracking	Silicon	$\|\eta\| < 2-2.5$	Silicon	$\|\eta\| < 3$
	Drif cell	$\|\eta\| < 1.1$	Fiber	$\|\eta\| < 1.7$
EM/HAD calorimeters	Scintillators	$\|\eta\| < 3.6$	LAr/DU	$\|\eta\| < 4$
Muon chambers	Drift/scint	$\|\eta\| < 1.5$	Drift/scint	$\|\eta\| < 2$

What is new since Winter 2011

CDF

- Addition data: $7.1 \to 8.2\,\mathrm{fb}^{-1}$
- Increase acceptance using narrowly separated lepton pairs
- Addition of $H \to ZZ \to 4\ell$ final state

D0

- Improve selection cuts
- 4^{th} generation interpretation

Both

- Update signal Branching ratios (S. Dittmaier et al arXiv:1101.0593)
- Updated $gg \to H$ scale uncertainty according (Stewart and Tackmann arXiv:1107.2117v1)

Search Strategy

I Use of all feasible final states

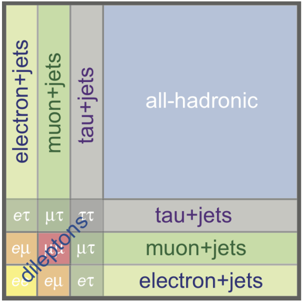
II Create as many sub-channels as possible

III Use of Multivariate (MVA) techniques

I: Use of all feasible final states

- Hadron collider environment requires at least one leptonic W decay
- Dilepton (e, μ) - BR$\sim 6\%$
  - Most sensitive final state
  - Lowest Background Rate
- Lepton $(e, \mu) + \tau_h$ - BR$\sim 4\%$
  - Consider hadronic τ decays (τ_h)
  - Provides additional sensitivity
  - Larger Background Rate
- e, μ+hadrons - BR$\sim 30\%$
  - Larger BR gives $\times \sim 5$ more signal compared to Dilepton
  - Large Background Rate

W Branching Fractions



II: Create as many sub-channels as possible

- Optimise searches for different mixtures of signal and backgrounds
- Dedicated Associated production searches
- CDF added new H→ZZ→4ℓ channel

Channel	CDF	DØ
	H→WW* $\to \ell^- \bar{\nu} \ell^+ \nu$	
$\ell = e, \mu$, 0/1/2+ jet	8.2 fb^{-1}	8.1 fb^{-1}
$\ell = e, \mu$, ≤ 1 jet low $M_{\ell\ell}$	8.2 fb^{-1}	-
$\ell = \tau_h, \mu(e)$	8.2 fb^{-1}	7.3 fb^{-1} (μ only)
$\ell = \tau_h, \mu(e)$, 2+ jet	-	4.3 fb^{-1}
	VH→VWW	
SS Dilepton	8.2 fb^{-1}	5.4 fb^{-1}
Trileptons	8.2 fb^{-1}	-
	H→WW→ $\ell \nu qq$	
$\ell = e, \mu$, 2+ jet	-	5.4 fb^{-1}
	H→ZZ→ 4ℓ	
$\ell = e, \mu$	8.2 fb^{-1}	-

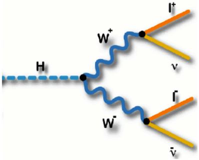
III: Use of Multivariate (MVA) techniques

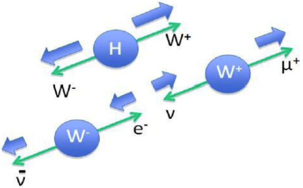
- Very low S/B - $(0.1-1.)\%$ for $m_H = 165\,\text{GeV}$ @ final selection
- Maximise power of discriminating variables
- Input parameters: Kinematic and Event topology variables
- MVA outputs used as inputs for limit setting (Neural Networks, Decision Trees)
- Technique validated measuring SM processes (see backup)

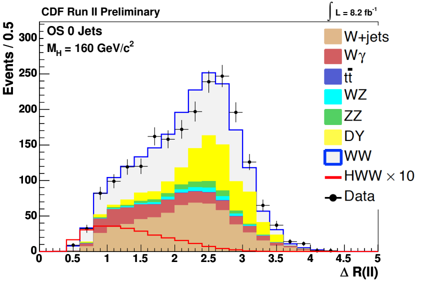
$H \rightarrow WW^* \rightarrow \ell^- \bar{\nu} \ell^+ \nu$

Event Selection

- 2 Opposite Sign high p_T isolated leptons distinguishes from multijet and W+jets
- Missing Energy from neutrinos distinguishes from Z/γ^*
- Final state topology due to spin 0 Higgs distinguishes from WW
  - Small opening angle between leptons in Higgs decays

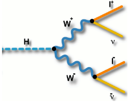




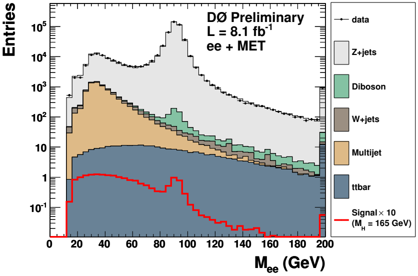


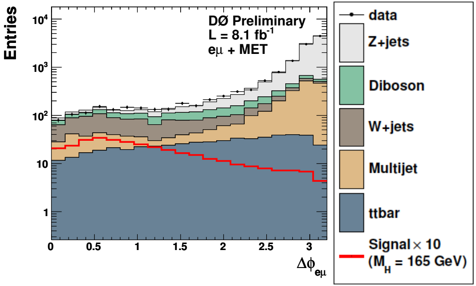
$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu \; (\ell = e, \mu)$

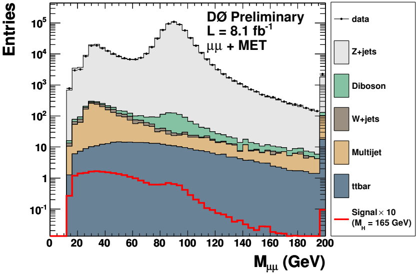
Splitting into sub-channels I



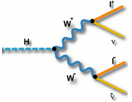
- Lepton Flavour
  - DØ: $e\mu, ee, \mu\mu$
  - CDF: Lepton flavour or quality
  - Separation gives high and low S/B regions
- Different efficiency, kinematics and resolution





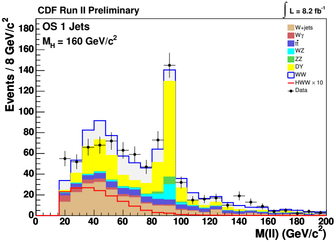


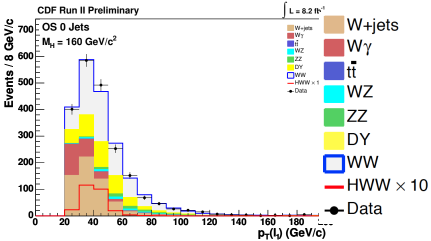
$H \rightarrow WW^* \rightarrow \ell^- \bar{\nu} \ell^+ \nu \ (\ell = e, \mu)$

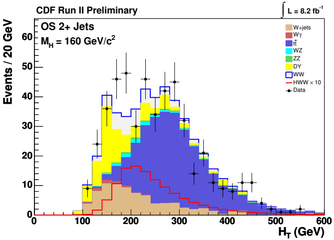


Splitting into sub-channels II

- Jet Multiplicity: 0jet, 1jet, $\geq$ 2jets
- Optimise on different signal/background compositions
  - 0jet: WW
  - 1jet: Z/γ^*,WW
  - 2jet: $t\bar{t}$

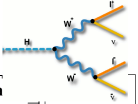




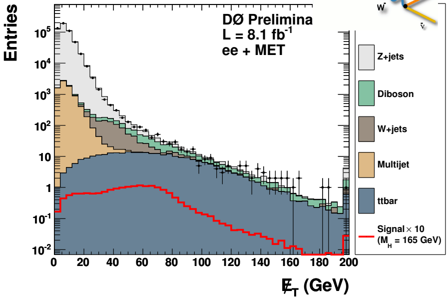


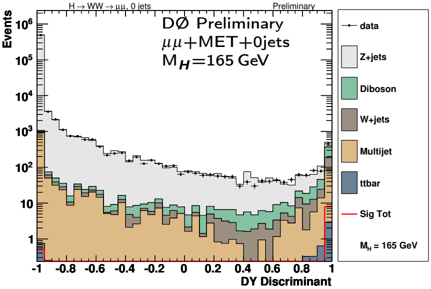
$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu \ (\ell = e, \mu)$

Final Event Selection

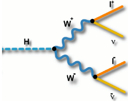


- Reduce large Z/γ^* using E_T^{miss} based vars
- DØ: Train DT against Z/γ^* for $ee,\mu\mu$
  - Each jet bin and mass hypothesis
  - E_T^{miss} related variables as inputs
  - Select events in high DT region
- CDF: Select events with high "real" E_T^{miss}
- **$\sim$100 signal evts at Final Selection (CDF+DØ) @$M_H = 165$ GeV**



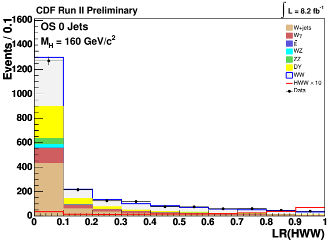


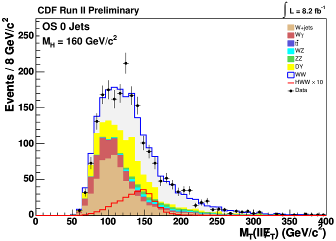
$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu \ (\ell = e, \mu)$



Extract Signal

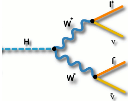
- Train MVA using Final Selection events in each jet bin and mass
- Input discriminating variables:
- Likelihood ratio of Matrix Element calculation (0jet CDF)
- Topological+kinematic combos
  - Transverse mass of vector sum of lepton p and E_T^{miss}
- Use b-tagging information as input variable or veto in 1 or 2jet bin against $t\bar{t}$

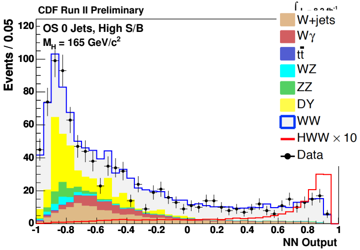


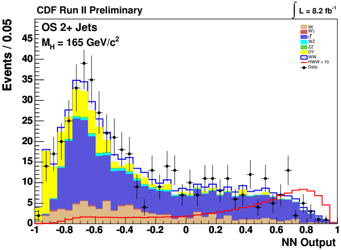


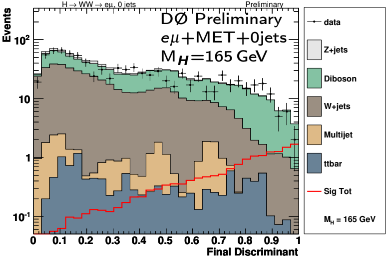
$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu \ (\ell = e, \mu)$

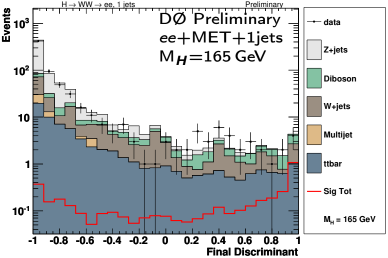
MVA distributions CDF: NN DØ: DT





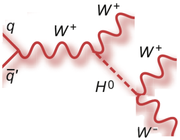


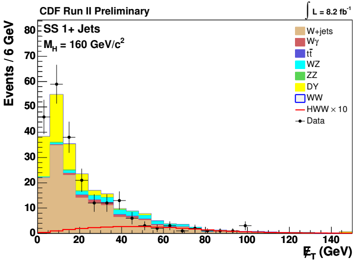


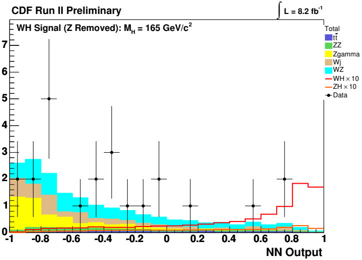


VH→VWW (V=W or Z)

Multi-lepton and jet final states from W/Z decays







- Suppress SM backgrounds
- Same Sign Dilepton + E_T^{miss}
  - WH→WWW
  - Lepton charge measurement important
- Trilepton OS same flavour pair in/out Z mass window
  - ZH→ZWW/WH→WWW

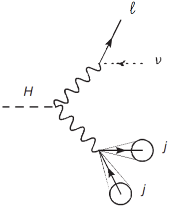
Other final States

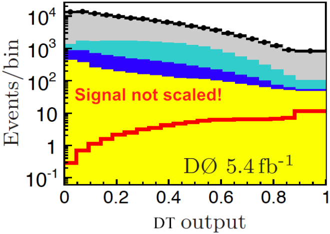
Including hadronic W decays

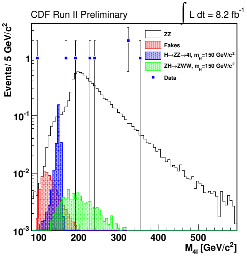
- **52 expected signal events @M_H=160 GeV!**
- Main background W+jets
- Reconstruct p_z of neutrino using W mass constraint
- Possible to extract Higgs mass for M_H >160 GeV

Including H$\to 4\ell$ ($\ell = e, \mu$)

- **Sensitive to H$\to$ZZ and ZH$\to$ZWW**
- $4e$,4μ,$2e2\mu$ final states
- Main background: SM *ZZ* production
- 4 lepton invariant mass used for limit setting

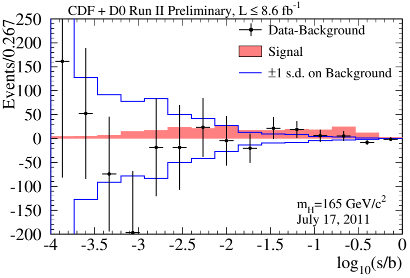






Systematic Uncertainties

- Affecting Normalization or Shape of signal and background
- Correlated luminosity (Total:6% Correlated:4%) and x-section between CDF and DØ
- Lepton ID $2-4\%$, Jet $3-25\%$(process dependent)



- $\sigma_{ggH}^{\mathrm{NNLO+NNLL}}$ scale variation
  - jet bin dependent
- $\sigma_{ggH}^{\mathrm{NNLO+NNLL}}$ PDF uncertainty
  - $8-30\%$ jet bin dependent
- Shape systematic by varying NNLO+NNLL p_T^H spectrum

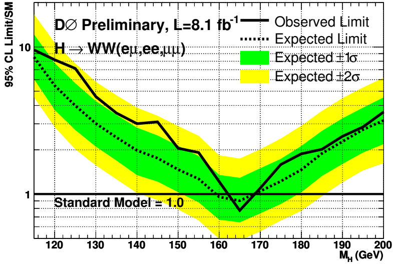
σ μ_R, μ_F	s_0	s_1	s_2
0jet	13.4%	-23.0%	-
1jet	-	35.0%	-12.7%
≥2jet	-	-	33.0%

Expected signal lies above background uncertainty!

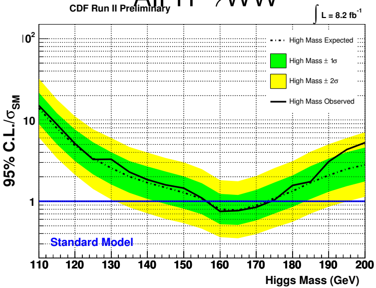
Limits

- No significant excess of signal like events is observed
- MVA outputs used to set exclusion limits at 95% C.L
  - See Weiming's talk for Tevatron combination!

OS dilepton



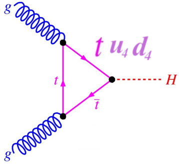
All H→WW



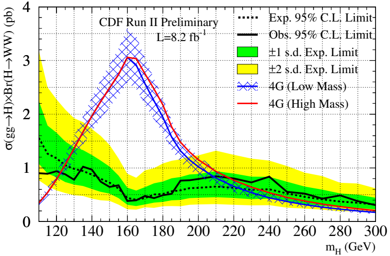
D0 High Mass exclusion (all channels)
161< M_H <170 @95% C.L
(159< M_H <170 expected)

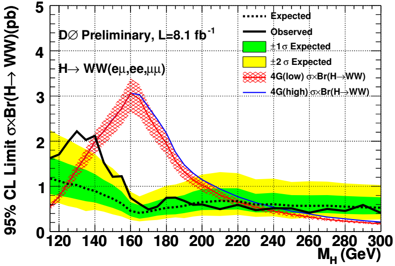
CDF High Mass exclusion (all channels)
156.7< M_H <173.3 @95% C.L
(157< M_H <172.2 expected)

4th Generation interpretation



- New heavy generation of quarks
- Boost gg→H x-section by factor of ∼ 9
- Optimise OS Dilepton searches on ggH and extened mass reach





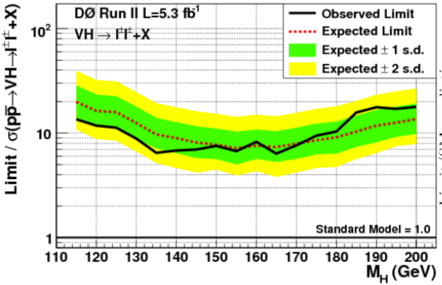
CDF: 123<M_H <215 @95% C.L

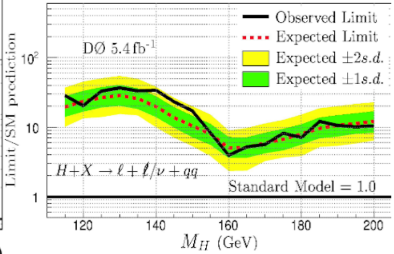
D0: 140<M_H <240 @95% C.L

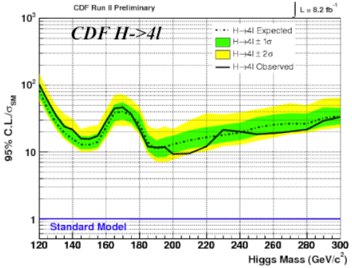
Conclusions and Outlook

- Presented an overview of the latest Tevatron High mass Higgs searches
  - Large Data Samples
  - All possible final states considered
  - All possible channel splittings considered
  - Sophisticated signal/background discriminants
- Still room for improvement
  - $10\,\text{fb}^{-1}$ available
  - Improvements in object ID
- Focus on improving performance for $m_H < 135\,\text{GeV}$
  - $3\times$SM Exp. for $m_H = 120\,\text{GeV}$ @95% C.L (CDF+D0)
  - Significant contribution to low and intermediate masses!
- Many thanks to CDF and DØ collaborators

Backup


DØ Run II L=5.3 fb^{-1}
VH → l±l±+X
Observed Limit
Expected Limit
Expected ± 1 s.d.
Expected ± 2 s.d.
Standard Model = 1.0
Limit / σ(pp̄→VH→l±l±+X)
M$_H$ (GeV)
110 120 130 140 150 160 170 180 190 200


DØ 5.4 fb^{-1}
Observed Limit
Expected Limit
Expected ±2s.d.
Expected ±1s.d.
$H+X \to \ell + \ell/\nu + qq$
Standard Model = 1.0
Limit/SM prediction
M_H (GeV)
120 140 160 180 200

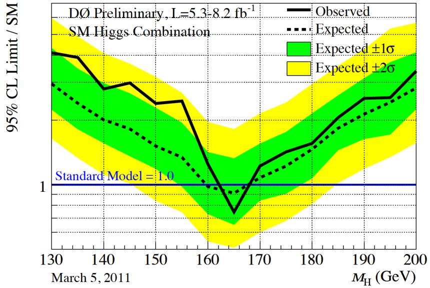

CDF Run II Preliminary
L = 8.2 fb^{-1}
CDF H->4l
H→4l Expected
H→4l ± 1σ
H→4l ± 2σ
H→4l Observed
Standard Model
95% C.L./σ$_{SM}$
Higgs Mass (GeV/c^2)
120 140 160 180 200 220 240 260 280 300

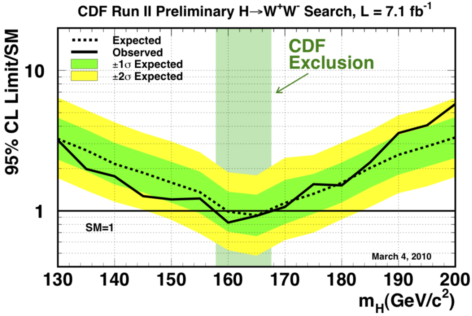
Background estimation

- **Diboson WW,WZ,ZZ:** MC, NLO x-sec and NLO p_T^{WW} distribution
- **Z/γ^*+jets:** MC, NNLO x-section, data based correction on z-p_T
- **W+jets:** W+γ: Data Driven model and/or MC with data based correction
- $t\bar{t}$: MC, NNLO x-section
- **QCD multijet:** Data Driven model

Winter 2011 result

- All High Mass channels combined
- MVA outputs used to set exclusion limits at 95% C.L





$163 < M_H < 168$ @95% C.L
($160 < M_H < 168$ expected)

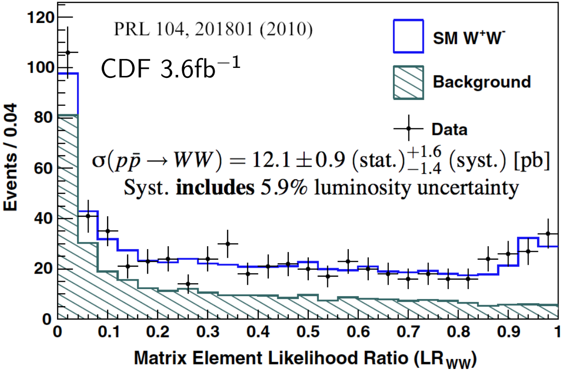
$158 < M_H < 168$ @95% C.L
($160 < M_H < 167$ expected)

Expected limits per channel

	Exp Limit x SM @165	
Channel	CDF	DØ
H→WW* $\rightarrow \ell^- \bar{\nu} \ell^+ \nu$		
$\ell = e, \mu$, 0/1/2+ jet	0.93 (incl. low $M_{\ell\ell}$,SS dilep,trilep)	0.97
$\ell = \tau_h, \mu(e)$	13.1	7.5 ($\mu\tau_h$)
$\ell = \tau_h, \mu(e)$, 2+ jet	-	12.3
H→WW→ $\ell \nu qq$		
$\ell = e, \mu$, 2+ jet	-	5.1
VH→VWW		
SS Dilepton	-	7.0

IV: Validate analysis techniques

- Use methodology of H→WW searches to measure WW x-section
- Excellent agreement to SM prediction



Matrix Element Discriminant

The probability density for any given mode m

$$P_m(x_{obs}) = \frac{1}{<\sigma_m>} \int \frac{d\sigma_m^{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

x_{obs}	are the observed "leptons" and $\vec{\not{E}}_T$,
y	are the true lepton four-vectors (including neutrinos),
σ_m^{th}	is the leading-order theoretical calculation of the cross-section for mode m,
$\epsilon(y)$	is the total event efficiency $\times$ acceptance,
$G(x_{obs}, y)$	is an analytic model of resolution effects, and
$\frac{1}{<\sigma_m>}$	is the normalization.

Event probability densities used to construct discriminant:

$$LR_S(x_{obs}) \equiv \frac{P_S(x_{obs})}{P_S(x_{obs}) + \Sigma_i k_i P_i(x_{obs})}, \quad \text{CDF Note 10432}$$

Responses I

Additional Theoretical Uncertainties

- Should there be an additional theoretical uncertainty assigned to our gluon fusion cross sections coming from the effective field theory (EFT) approach used to integrate electroweak contributions from heavy and light loop particles?
- Such an uncertainty is already included:

  C. Anastasiou, R. Boughezal, F. Petriello, JHEP **0904**, 003 (2009). [arXiv:0811.3458 [hep-ph]].

- Uncertainties on the gluon fusion cross section used in Tevatron Higgs searches incorporate a ~2% level component to account for this effect
- The same authors find that when they entirely remove corrections from light quark diagrams (clearly too conservative), the total cross section changes by less than 4%
- **Our current treatment of EFT effects is on solid ground**

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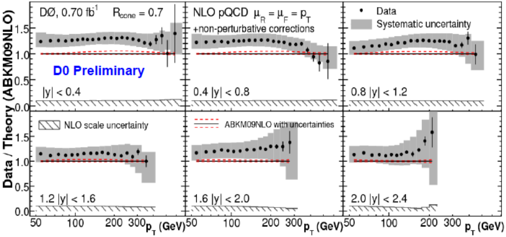
Responses II

PDF Uncertainties

- Should our PDF uncertainties account for observed differences in cross sections obtained using our default MSTW model and ABKM/HERAPDF models?
- See Juan Rojo's talk on "Recent Developments and Open Problems in Parton Distributions" in the Tuesday afternoon session
- ABKM09 & HERAPDFs do not include Tevatron data, which provide the best constraints on the relevant high-x gluon distributions at Tevatron energies
- A comparison of high E_T Tevatron data with ABKM09 & HERAPDF shows large disagreement:

ABKM09 at the Tevatron:
Ratio of D0 High-ET jet cross-section to ABKM09 prediction
(Data vs central PDF value)

(→ Uncertainty on ABKM Prediction)



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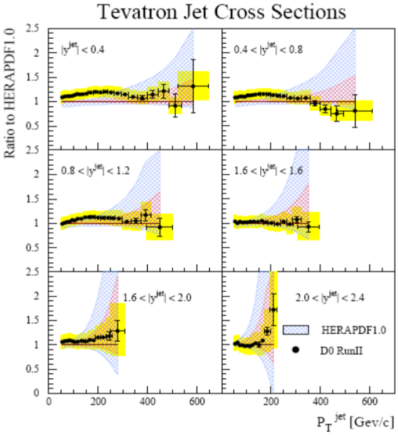
Responses III

PDF Sets



HERAPDF1.0 at the Tevatron:
Ratio of D0 High-ET jet cross section to HERAPDF1.0 prediction (Data vs central PDF value)

→ Total PDF uncertainty
→ Experimental PDF uncertainty
→ Systematic experimental error

- Our choice is also consistent with recommendations by the PDF4LHC working group, which is charged to provide guidance to experiments with respect to the use of PDF sets: http://www.hep.ucl.ac.uk/pdf4lhc/
- **Our PDF uncertainties are appropriate**

H1 & Zeus collaborations:
https://www.desy.de/h1zeus/combined_results/benchmark/tev.html

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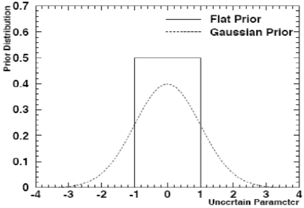
Responses IV

Treatment of Theoretical Uncertainties

- Most theoretical uncertainties are rather loosely stated. They are interpreted in terms of a maximum range of variations (*flat prior*)
- We treat theoretical uncertainties as gaussian (*gaussian prior*)
- Are we underestimating our uncertainties?
- We use the maximum bound as 1σ. This means we allow even larger variations than the given bounds. (See figure)
- We also tested the flat prior approach and found no significant change in our limits M. Buehler o.b.o TEVNPHWG La Thuille 2011
- **We are not underestimating our uncertainties**



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Responses V

Emulation of Tevatron Limit Calculation

- Care needs to be taken when trying to emulate Tevatron limits
- Correlations between different input channels need to be properly taken into account:
  - Our limit calculation uses these correlations to constrain the backgrounds
  - Our backgrounds are better constrained by the data, as compared to the theory. This can be viewed as a measurement of the true rate and the a posteriori uncertainty is an experimental determination of the true error.
- An estimation of the sensitivity increase due to MVA is not straightforward:
  - Our pre-selection cuts are kept as loose as possible to maximize signal acceptance and cannot be interpreted as an optimized cut-based analysis
  - MVAs are used to separate signal from background
  - To estimate MVA sensitivity gains: compare fully optimized cut-based results with MVA results
  - MVAs typically improve limits by ~30% over optimized cut-based
- Impact of theoretical uncertainties:
  - Theoretical uncertainties are statistically accounted for together with other systematics
  - Increasing theoretical cross section uncertainties is not equivalent to decreasing the central prediction

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