The Tevatron's Search for High Mass Higgs Bosons

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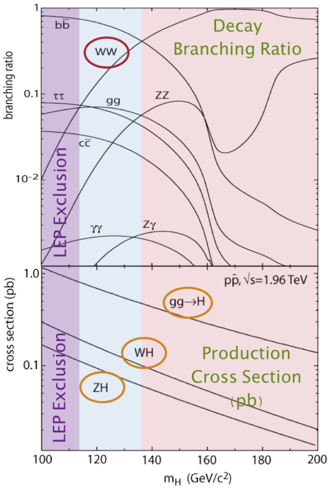
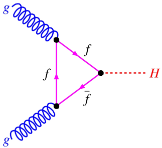
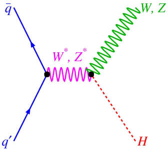
On behalf of the CDF and DØ Collaborations

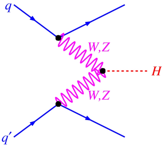
High mass Higgs searches at the Tevatron

- Higgs production cross sections for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
  - Gluon fusion (ggH) $\sigma \approx 0.2 - 1$ pb
  - Associated production (VH) $\sigma \approx 0.01 - 0.3$ pb
  - Vector Boson Fusion (qqH) $\sigma \approx 0.01 - 0.1$ pb
- Precision ewk data yields $114 < M_H < 186$ GeV @95 C.L
- High Mass definition: Searches most sensitive for $M_H \geq 135$ GeV
  - Main Decay mode is WW





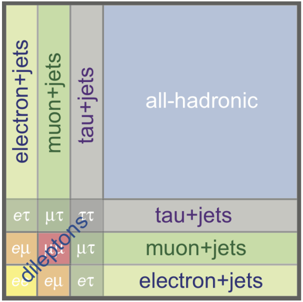




H→WW* Final States

- **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

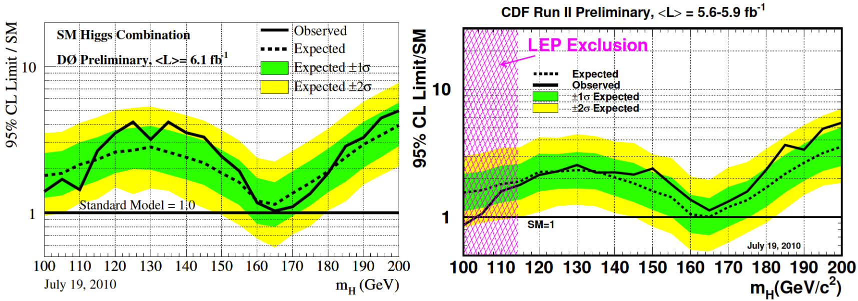


High Masss Higgs Search Strategy

- Very low S/B makes a cut based analysis impossible
  - $(0.1-1.)\%$ for $m_H = 165\,\text{GeV}$ @ final selection stage
  - Not a counting experiment
- **Employ use of Multivariate techniques (MVA) to extract the signal**
  - 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
- **Create as many sub-channels as possible**
  - Optimise our Signal/Background discriminants for different mixes of signal and background contributions

Status in Summer 2010

- Combining low mass and high mass



- DØ almost achieved observed exclusion at $M_H = 165$ GeV
- CDF achieved excpected exclusion at $M_H = 165$ GeV
- Work even harder to improve sensitivity !

What is new in March 2011

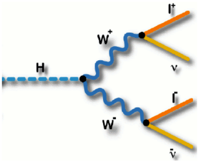
- CDF and DØ updated High Mass program using up to 7.1 fb^{-1} and 8.2 fb^{-1} respectively

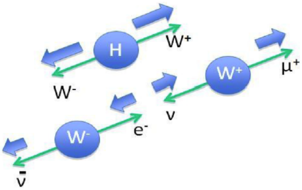
Channel	CDF	DØ
	$\mathbf{H \to WW^*} \to \ell^- \bar{\nu} \ell^+ \nu$	
$\ell = e, \mu$, 0/1/2+ jet	Add data	New
$\ell = e, \mu$, ≤ 1 jet low $M_{\ell\ell}$	Add data	-
$\ell = \tau_h, \mu(e)$	Add data	New
$\ell = \tau_h, \mu(e)$, 2+ jet	-	New (4.3 fb^{-1})
	$\mathbf{H \to WW} \to \ell \nu q q$	
$\ell = e, \mu$, 2+ jet	-	(5.4 fb^{-1})
	VH→VWW	
SS Dilepton	Add data	(5.4 fb^{-1})
Trileptons	Add data	-

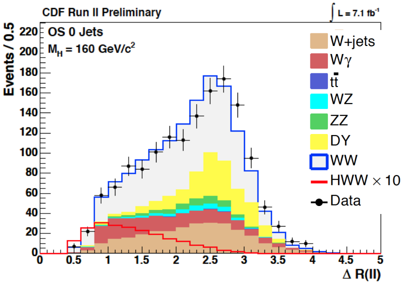
$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu$

Event Selection

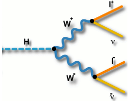
- 2 Opposite Sign high p_T isolated leptons distinguishes from multijet and W+jets
- Missing Energy from neutrinos distinguishes from Z/γ^*
- Final state topology due to spin 0 Higgs distinguishes from WW
  - Small opening angle between leptons in Higgs decays





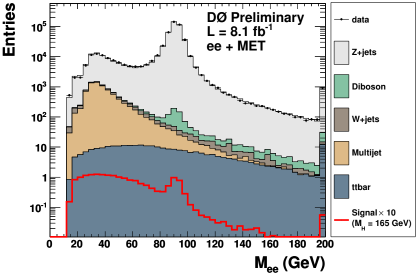


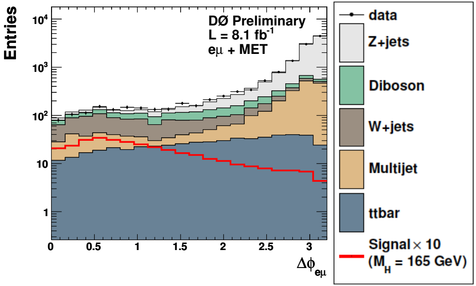
$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu \ (\ell = e, \mu)$

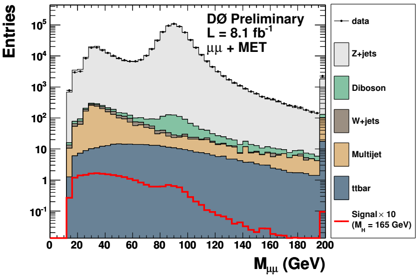


Splitting into sub-channels I

- 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







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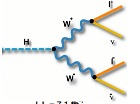
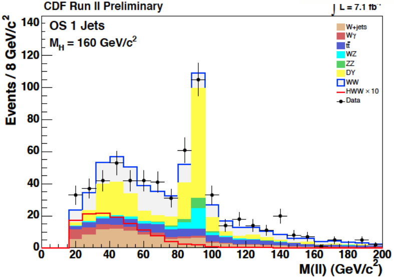
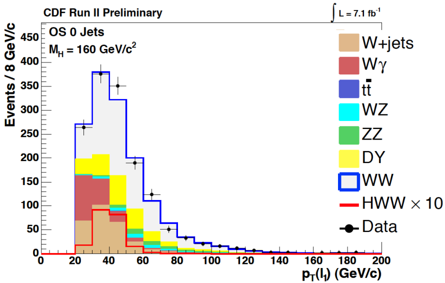
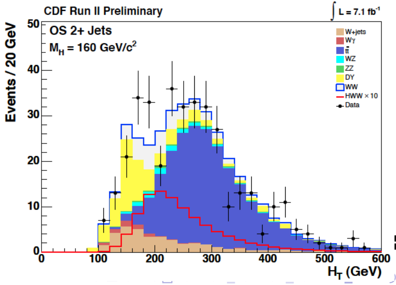


Splitting into sub-channels II

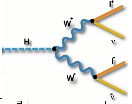
- Jet Multiplicity: 0jet, 1jet, $\geq$ 2jets
- Optimise on different signal/background compositions
  - 0jet: WW
  - 1jet: Z/γ^*
  - 2jet: $t\bar{t}$







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

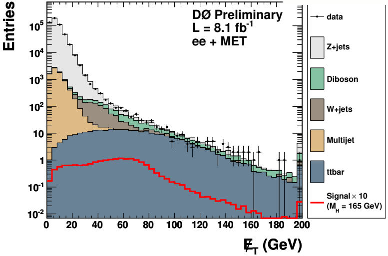


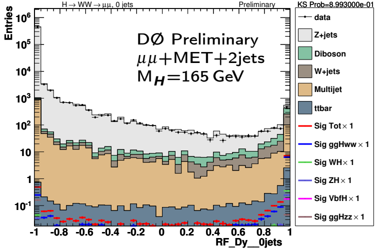
Final Event Selection

e

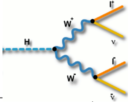
- Reduce large Z/γ^* using E_T^{miss}
- DØ: Train DT against Z/γ^* for $ee, \mu\mu$
  - Each jet bin and mass hypothesis
  - E_T^{miss} related variables as inputs
  - Select events in high DT region
- CDF: Select events with high E_T^{miss}

- **$\sim$100 signal evts at Final Selection (CDF+DØ) @$M_H = 165$ GeV**
- **Jet bin splitting and Z/γ^* DT improves DØ's expected sensitivity**
  - **30% @M_H=130GeV**
  - **15% @M_H=165GeV**



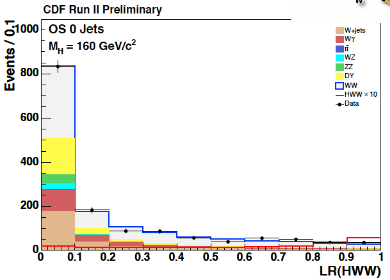


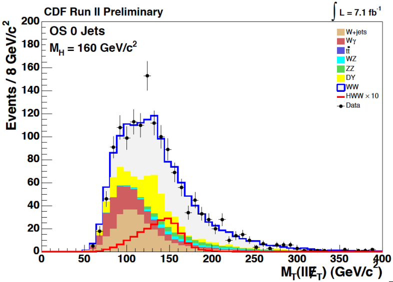
$H \rightarrow WW^* \rightarrow \ell^- \bar{\nu} \ell^+ \nu \ (\ell = e, \mu)$



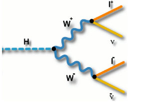
Extract Signal

- 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 $t\bar{t}$

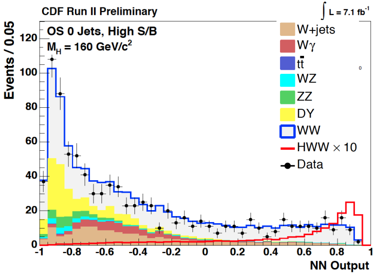


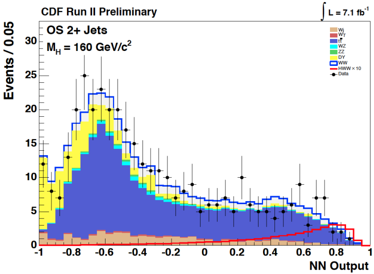


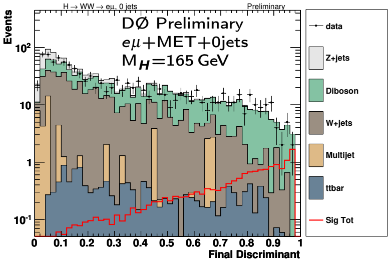
$H \rightarrow WW^* \rightarrow \ell^- \bar{\nu} \ell^+ \nu \; (\ell = e, \mu)$

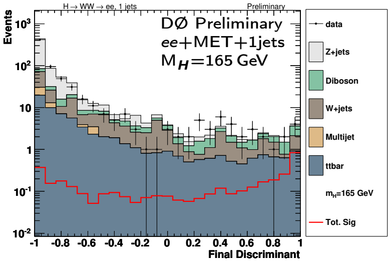


MVA distributions CDF: NN DØ: DT

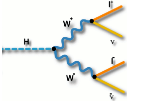






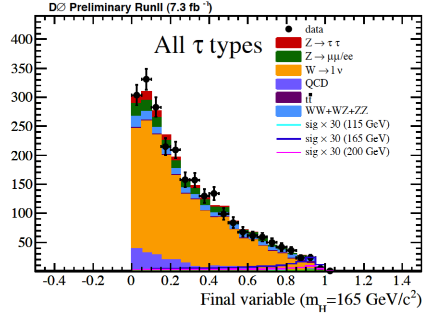


$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu$ ($\ell_1 = \tau_h$ $\ell_2 = \mu, e$)

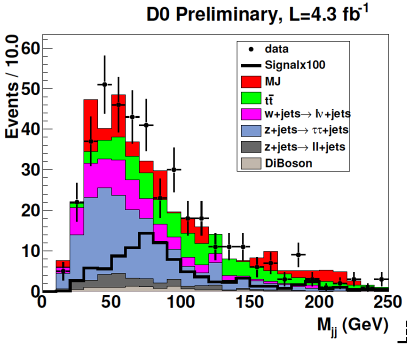


Including τ leptons decaying to hadrons. New channels for DØ!
CDF updated $e + \tau_h$ and $\mu + \tau_h$ as well

- μ and hadronically decaying τ (τ_h) + $\leq$1jet
- 3 subchannels based on τ_h track/calo structure
- MVA based on NN



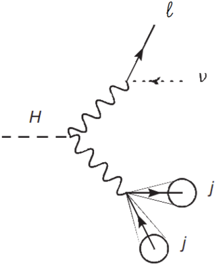
- $\mu\tau_h$ and $e\tau_h$ + $\geq$2jet
- For $M_H < 135$ sensitive to $H \to \tau\tau$ final state

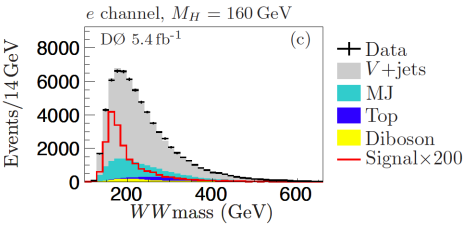


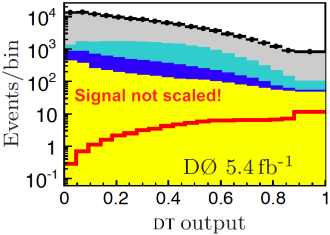
$H \rightarrow WW^* \rightarrow \ell \nu q \bar{q}' \; (\ell = e, \mu)$

Including hadronic W decays

- 1 lepton $\geq$ 2jets+E_T^{miss}
- **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

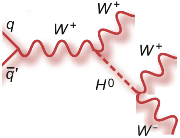


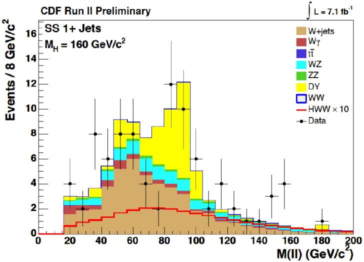


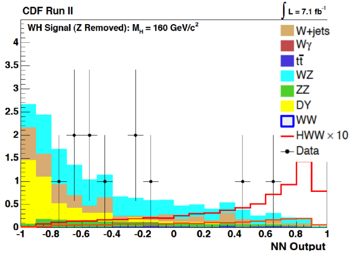


VH→VWW (V=W or Z)

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



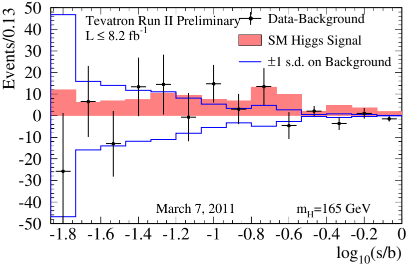




- Suppress SM backgrounds
- Same Sign Dilepton + E_T^{miss}
  - WH→WWW
  - Lepton charge measurement important
- Trilepton OS same flavour pair in/out Z mass window
  - ZH→ZWW/WH→WWW

Systematic Uncertainties

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

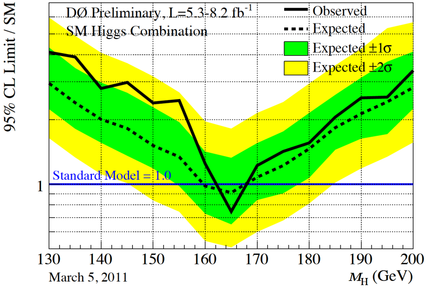


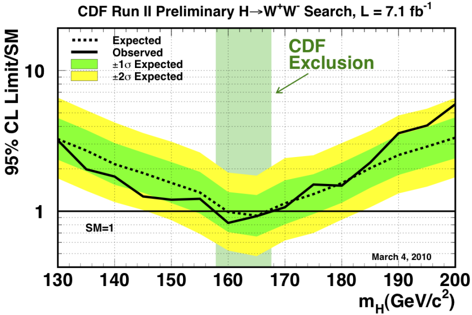
- $\sigma_{ggH}^{\mathrm{NNLO+NNLL}}$ scale variation
  - $7-33\%$ jet bin dependent
  - JHEP **0908**, 099 (2009), Phys Rev D **81,** 074023 (2010)
- $\sigma_{ggH}^{\mathrm{NNLO+NNLL}}$ PDF uncertainty
  - $8-30\%$ jet bin dependent
  - Treatment recommended by PDF4LHC group
- Shape systematic for resummation scale by varying NNLO+NNLL p_T^H spectrum

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





DØ: Single Experiment Exclusion!!

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

CDF: Single Experiment Exclusion!!

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

Conclusions and Outlook

- Presented an overview of the latest Tevatron High mass Higgs searches
- A great milestone achieved by both experiments reaching exclusion sensitivity individually
- Explore all available avenues
  - Large Data Samples
  - All feasible final states considered
  - All feasible channel splittings considered
  - Sophisticated signal/background discriminants
- Still room for improvement
  - $10\,\mathrm{fb}^{-1}$ by the end of RunII
  - Improvements in object IDs
  - Additional channels such as $H\rightarrow ZZ$
- And now for the Combined Results! (see Bo's talk coming soon)
- Many thanks to CDF and DØ collaborators

Backup

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

Matrix Element Discriminant

The probability density for any given mode m

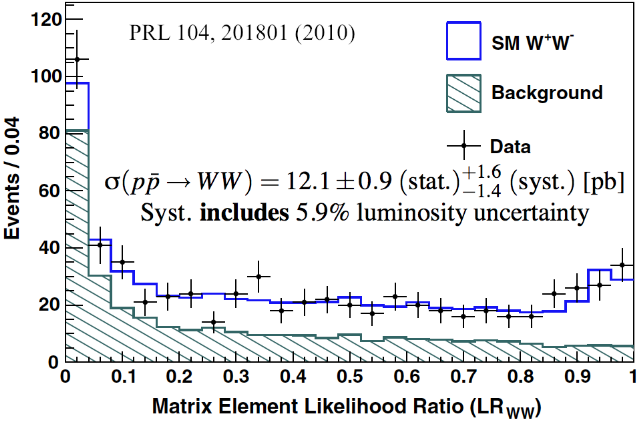
$$P_m(x_{obs}) = \frac{1}{<\sigma_m>} \int \frac{d\sigma_m^{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

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:

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

MVA cross check



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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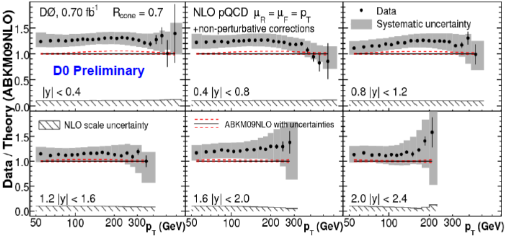
Responses II

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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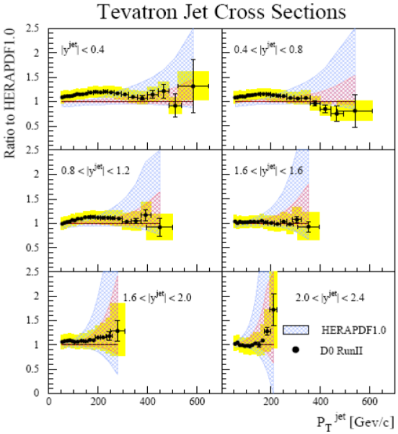
Responses III

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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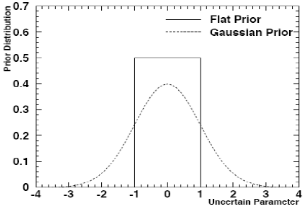
Responses IV

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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