Search for the Higgs at the Tevatron

Jonathan Hays

Séminaires de physique corpusculaire
DPNC, Université de Genève
Outline

Higgs boson
Tevatron
SM Searches
BSM searches
Conclusions
Higgs Boson

Makes the SM work
allows massive W & Z
allows fermion masses

Testable prediction of Electroweak theory

Scalar Higgs Boson
MSSM (2 doublet)

5 Higgs Bosons

(Explains very little)
Higgs Production and Decay

Gluon fusion dominates difficult backgrounds triggering problematic

Associated production lower rate clearer signature (leptonic decays of W/Z)
Higgs Constraints and Limits
Higgs Constraints and Limits

Tevatron Run II Preliminary, $\langle L \rangle = 5.9 \text{ fb}^{-1}$

Tevatron limits as of last summer...
Tevatron

Proton-antiproton collider

Centre of mass energy of 1.96 TeV

396ns bunch spacing

RunII will end later this year
Luminosity

Project around 10fb\(^{-1}\) recorded lumi with running until September
Detectors

Silicon vertex detector
Wire drift chamber
Pb/Fe-scintillator calorimetry
Muon chambers

Silicon vertex detector
Scintillating fibre tracker
LAr-U calorimetry
Muon chambers
SM HIGGS SEARCHES
HIGH MASS
LOW MASS
Search Strategy

Analyze final states with clear signatures:
- electrons
- muons
- displaced vertices (b-jets)
- missing energy (neutrinos)

Combine as many channels as possible
Combine across experiments
Search Strategy

Most important at low mass

Most important at high mass
# Search Strategy

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity ( fb(^{-1}))</th>
<th>(m_H) range ( GeV/(c^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(WH \rightarrow \ell\nu b\bar{b}) 2-jet channels</td>
<td>5.7</td>
<td>100-150</td>
</tr>
<tr>
<td>(WH \rightarrow \ell\nu b\bar{b}) 3-jet channels</td>
<td>5.6</td>
<td>100-150</td>
</tr>
<tr>
<td>(ZH \rightarrow \nu\bar{\nu} b\bar{b})</td>
<td>5.7</td>
<td>100-150</td>
</tr>
<tr>
<td>(ZH \rightarrow \ell^+\ell^- b\bar{b})</td>
<td>5.7</td>
<td>100-150</td>
</tr>
<tr>
<td>(H \rightarrow W^+W^-) 2(\times)(0,1 jets)+(2+ jets)+(low-(m_\ell))+(e-(\tau_{had}))+((\mu-\tau_{had}))</td>
<td>5.9</td>
<td>110-200</td>
</tr>
<tr>
<td>(WH \rightarrow WW^+W^-) (same-sign leptons 1+ jets)+(tri-leptons)</td>
<td>5.9</td>
<td>110-200</td>
</tr>
<tr>
<td>(ZH \rightarrow ZW^+W^-) (tri-leptons 1 jet)+(tri-leptons 2+ jets)</td>
<td>5.9</td>
<td>110-200</td>
</tr>
<tr>
<td>(H + X \rightarrow \tau^+\tau^-) (1 jet)+(2 jets)</td>
<td>2.3</td>
<td>100-150</td>
</tr>
<tr>
<td>(WH + ZH \rightarrow jjb\bar{b}) 2(\times)(TDT,LDT)</td>
<td>4.0</td>
<td>100-150</td>
</tr>
<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>5.4</td>
<td>100-150</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity ( fb(^{-1}))</th>
<th>(m_H) range ( GeV/(c^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(WH \rightarrow \ell\nu b\bar{b}) (ST,D,T,2,3 jet)</td>
<td>5.3</td>
<td>100-150</td>
</tr>
<tr>
<td>(VH \rightarrow \tau^+\tau^- b\bar{b}/qq\tau^+\tau^-)</td>
<td>4.9</td>
<td>105-145</td>
</tr>
<tr>
<td>(ZH \rightarrow \nu\bar{\nu} b\bar{b}) (ST,TLD)</td>
<td>5.2-6.4</td>
<td>100-150</td>
</tr>
<tr>
<td>(ZH \rightarrow \ell^+\ell^- b\bar{b}) (ST,D,T,(ee,\mu\mu,e\epsilon_{ICR},\mu\mu_{trk}))</td>
<td>4.2-6.2</td>
<td>100-150</td>
</tr>
<tr>
<td>(VH \rightarrow \ell^+\ell^- \pm X)</td>
<td>5.3</td>
<td>115-200</td>
</tr>
<tr>
<td>(H \rightarrow W^+W^- \rightarrow e\pm\nu\mp\nu, \mu\pm\nu\mp\nu)</td>
<td>5.4</td>
<td>115-200</td>
</tr>
<tr>
<td>(H \rightarrow W^+W^- \rightarrow e\pm\nu\mp\nu) (0,1,2+ jet)</td>
<td>6.7</td>
<td>115-200</td>
</tr>
<tr>
<td>(H \rightarrow W^+W^- \rightarrow \ell\nu jj)</td>
<td>5.4</td>
<td>130-200</td>
</tr>
<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>4.2</td>
<td>100-150</td>
</tr>
<tr>
<td>(ttH \rightarrow ttb\bar{b}) (ST,D,T,T,4,5+ jets)</td>
<td>2.1</td>
<td>105-155</td>
</tr>
</tbody>
</table>

(As of summer 2010)
# Search Strategy

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb$^{-1}$)</th>
<th>$m_H$ range (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow 2\times(0,1 \text{ jets}) + (2+ \text{ jets}) + (\text{low-} m_{\ell\ell}) + (e - \tau_{\text{had}}) + (\mu - \tau_{\text{had}})$</td>
<td>7.1</td>
<td>110-200</td>
</tr>
<tr>
<td>$WH \rightarrow WW+W^- \rightarrow (\text{same-sign leptons}) + (\text{1+ jets}) + (\text{tri-leptons})$</td>
<td>7.1</td>
<td>110-200</td>
</tr>
<tr>
<td>$ZH \rightarrow ZW^+W^- \rightarrow (\text{tri-leptons}) + (\text{1 jet}) + (\text{tri-leptons})$</td>
<td>7.1</td>
<td>110-200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb$^{-1}$)</th>
<th>$m_H$ range (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow l^{\pm}\nu l^{\mp}\nu$</td>
<td>8.1</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \mu\nu\tau_{\text{had}}\tau_{\text{had}}\nu$</td>
<td>7.3</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu$</td>
<td>5.4</td>
<td>115-200</td>
</tr>
<tr>
<td>$VH \rightarrow \ell^{\pm}\ell^{\mp} + X$</td>
<td>5.3</td>
<td>115-200</td>
</tr>
<tr>
<td>$VH \rightarrow \tau^+\tau^-bb/qq\tau^+\tau^-$</td>
<td>5.3</td>
<td>105-200</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>8.2</td>
<td>100-150</td>
</tr>
</tbody>
</table>

Updated for combinations for Winter conferences 2011
High Mass Searches

High mass: \( m_H > 135 \text{ GeV} \)
Dominated by: \( H \rightarrow WW \)

Dilepton (e and \( \mu \)): (~6%)
most sensitive
lowest background rate

Lepton + hadronic tau: (~4%)
brings additional sensitivity
larger backgrounds

Lepton + jets: (30%)
lots more signal
huge backgrounds

21/03/2011
Jonathan Hays
High Mass Searches

Separate in many sub-channels:

- **lepton flavour/quality:**
  - ee, eμ, μμ (D0)
  - high S/B, low S/B (CDF)

- **lepton charge:**
  - OS & SS

- **jet multiplicity:**
  - 0, 1 and >= 2
  - low and high dilepton mass (CDF)

Use MVA techniques – optimised in each sub-channel

<table>
<thead>
<tr>
<th>electron+jets</th>
<th>muon+jets</th>
<th>tau+jets</th>
<th>all-hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>eτ</td>
<td>μτ</td>
<td>ττ</td>
<td>tau+jets</td>
</tr>
<tr>
<td>eμ</td>
<td>μμ</td>
<td>μτ</td>
<td>muon+jets</td>
</tr>
<tr>
<td>eε</td>
<td>eμ</td>
<td>eτ</td>
<td>electron+jets</td>
</tr>
</tbody>
</table>
Dileptons

Select 2 OS leptons + Missing Energy
Spin 0 Higgs $\rightarrow$ difference in lepton opening angle from WW production
Dileptons: subchannels

CDF: 6 subchannels

0/1/2+ jets

high/low S/B lepton categories
di-lepton mass

Dominant backgrounds:

0j: WW
1j: DY and WW
2+j: top

Low dilepton mass: $W\gamma$
Dileptons: subchannels

DO: 18 subchannels:
lepton flavour: ee, eμ, μμ
jet multiplicity: 0,1,2+

DT trained to suppress Z/γ*
Further DT trained to suppress other backgrounds

Dominant backgrounds:
ee – Z/γ* → ee
μμ – Z/γ* → μμ
eμ – WW, W+jets
Other channels

H→WW→lντ_HADν
CDF: BDT kinematics+τ ID
D0: NN τ ID + NN final selection

H→WW→lvjj
D0: huge W/Z+jets background
Random Forest selection
(CDF result coming soon)

CDF:
SS leptons + jets
3 trilepton channels
Experimental Uncertainties

Generally uncorrelated across experiments
Many correlated across channels at a single experiment

Lepton and jet selection efficiencies
Jet energy scale
QCD ISR/FSR effects
Missing ET modeling
Theoretical Uncertainties I

Canonical scale variation $\kappa=2$
Uncertainties taken from NNLO calculation - conservatively cover NLO and NNLO calculations
Investigations at NNNLO show no unexpected behaviour
Evaluated separately and correlated across jet categories and experiments (7-33%)

$gg\rightarrow h$ dominant process
Grazzini, de Florian (arXiv:0901.2427)
Anastasiou, Boughezal, Periello (arXiv:0811.3458)
- resummed NNLL+NNLO

Included as uncertainties in the limit setting

Jonathan Hays
MSTW2008 NNLO PDFs (Eur.Phys.J. C 63, 189)
Global parton fit including Tevatron jet data
(important for constraining high-x gluon)

Includes uncertainties on $\alpha_s$ following MSTW procedure

Follow prescription from PDF4LHC : ~factor 2 increase w.r.t. using MSTW08 errors alone. (2.5-30% @ $m_h$=160 GeV)

PDF depends on scale choice - effect included in scale uncertainties ensures correct correlations

Correlated across experiments and channels

Further details on combinations: http://tevnphwg.fnal.gov
Techniques: Limit setting

Two statistical approaches employed
Agreement better than 5% over all masses (average 2%)

1. Bayesian
   Flat prior for signal, credibility intervals
2. Modified frequentist
   Log-likelihood ratio, $\text{CL}_s = \text{CL}_s + \frac{b}{\text{CL}_b}$

Operate on binned final discriminant distributions
Poisson statistics assumed for each bin
Systematics introduced as nuisance parameters
Impact of systematics mitigated with constraints from data
# High Mass Summary

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lumi</th>
<th>Exp. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS, 0j</td>
<td>7.1</td>
<td>1.52</td>
</tr>
<tr>
<td>OS, 1j</td>
<td>7.1</td>
<td>2.13</td>
</tr>
<tr>
<td>OS +2j</td>
<td>7.1</td>
<td>2.74</td>
</tr>
<tr>
<td>Low M$_{ll}$</td>
<td>7.1</td>
<td>10.6</td>
</tr>
<tr>
<td>SS</td>
<td>7.1</td>
<td>2.75</td>
</tr>
<tr>
<td>Trileptons</td>
<td>7.1</td>
<td>4.9</td>
</tr>
<tr>
<td>e/µ+τ$_{HAD}$</td>
<td>7.1</td>
<td>13.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lumi</th>
<th>Exp. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS - eµ</td>
<td>8.1</td>
<td>1.26</td>
</tr>
<tr>
<td>OS - ee</td>
<td>8.1</td>
<td>2.29</td>
</tr>
<tr>
<td>OS - µµ</td>
<td>8.1</td>
<td>2.23</td>
</tr>
<tr>
<td>lνqν</td>
<td>5.4</td>
<td>5.1</td>
</tr>
<tr>
<td>SS</td>
<td>5.4</td>
<td>7.0</td>
</tr>
<tr>
<td>e/µ+τ$_{HAD}$ &lt;= 1j</td>
<td>7.3</td>
<td>7.8</td>
</tr>
<tr>
<td>e/µ+τ$_{HAD}$ &gt;= 2j</td>
<td>7.3</td>
<td>12.3</td>
</tr>
</tbody>
</table>

**CDF: 12 channels – all updated**

**D0: 34 channels – added hadronic tau channels**

Expected limits given for $M_A = 165$ GeV
Results

Combinations by experiment: single experiment exclusion from both CDF and D0
Results
Combined Results

SM Higgs excluded at 95% CL for $158 < m_h < 173$ GeV

Expected exclusion at 95% CL $153 < m_h < 179$ GeV

(Summer 2010 expected exclusion: $156 < m_h < 173$ GeV)
Projections
Luminosity alone insufficient to get exclusion across mass range

Analysis improvements needed:
- increase acceptance
- add channels
- advanced techniques
- improved b-tagging
With each update sensitivity has improved beyond that from luminosity alone
Acceptance

e.g. expand trigger and analysis acceptance for electrons and muons
Acceptance and trigger improvements: ZH→μμbb

More inclusive trigger selection

Relaxed kinematic cuts + NN selection
Improvements

25% improvement beyond luminosity at 115 GeV!
Adding channels: $H \rightarrow \tau\tau + \text{jets}$

$H \rightarrow \tau\tau + \text{jets}$: look for one hadronic tau decay + one leptonic

D0 update adds $e\tau$ final state and extra luminosity
Adding channels

15% improvement beyond luminosity alone
Advanced techniques: Multivariate analysis

Neural networks - the old workhorse

Matrix elements - use differential cross sections of signal and major backgrounds to estimate signal likelihood

Boosted decision trees
Random forests - gain by recovering events removed in traditional “cut-based analyses”

Use discriminant distribution (rather than say invariant mass or other kinematic dist.)
Multivariate techniques:

\[ H \rightarrow \gamma\gamma \]

Previous version of analysis (4.2 fb\(^{-1}\)) – used \( \gamma\gamma \)-invariant mass distribution

Update (8.2 fb\(^{-1}\)) uses decision tree distribution
Multivariate techniques:

\[ H \rightarrow \gamma \gamma \]

\[ \sim 20\% \text{ increase in sensitivity beyond luminosity increase alone} \]
Improved b-tagging

Since $H \rightarrow bb$ dominant at low mass – b-jet identification critical
Improved b-tagging: $ZH \rightarrow \nu\nu bb$

b-tagging improves discrimination
b-tagging discriminant input into final analysis discriminant
Improved b-tagging: $ZH \rightarrow \nu \nu bb$

MVA b-tagging + use of MVA in final discriminant -> 15% improvement over luminosity alone
## Low Mass Searches

<table>
<thead>
<tr>
<th></th>
<th>CDF Searches</th>
<th>D0 Searches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lumi</td>
<td>Exp. Limit</td>
</tr>
<tr>
<td>WH→lνbb</td>
<td>5.7</td>
<td>3.5</td>
</tr>
<tr>
<td>ZH→ννbb</td>
<td>5.7</td>
<td>4.0</td>
</tr>
<tr>
<td>ZH→llbb</td>
<td>5.7</td>
<td>5.5</td>
</tr>
<tr>
<td>VH/VBF→bbjj</td>
<td>4.0</td>
<td>17.8</td>
</tr>
<tr>
<td>H/VH/VBF→ττjj</td>
<td>2.3</td>
<td>24.5</td>
</tr>
<tr>
<td>H→γγ</td>
<td>4.2</td>
<td>20.8</td>
</tr>
<tr>
<td>ttH→ttbb</td>
<td></td>
<td>2.1</td>
</tr>
</tbody>
</table>

Latest results and updates:
- [http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm](http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm)

Updated since last summer
No new combination for Winter conferences – expect updates by Summer
NEW RESULTS IN BSM HIGGS
MSSM Neutral Higgs

Enhancement to “down-type” fermions

\[ \text{BR}(\phi \to bb) \sim 90\% \]
\[ \text{BR}(\phi \to \tau\tau) \sim 10\% \]

- \( b\phi \to 3b/b\tau\tau \)
- \( \phi \to \tau\tau \) clean signatures but low BR
- \( b\phi \to b\tau\tau \) reduced backgrounds
- \( bb\phi \to 4b/bb\tau\tau \) added sensitivity at low mA
- \( bb\phi \to bbb \) large background
- \( bb\phi \to 4b/bb\tau\tau \) high BR
Inclusive Searches

\[ \phi \rightarrow \tau \tau \]

\[ \sigma \times BR(\phi \rightarrow \tau \tau) \text{ (pb)} \]

- Combined Exp.
- Combined Obs.
- RunIIa Exp.
- RunIIa Obs.

95% C.L. upper limits

\[ \phi \rightarrow \tau \tau \]

\[ m(A), \text{ GeV/c}^2 \]

- observed
- expected

\[ \pm 1\sigma \]

\[ \pm 2\sigma \]
Inclusive Searches

Tevatron combination

http://arxiv.org/abs/1003.3363v3
Exclusive Searches

Published results from DØ


Searches in tau final states

4.3 fb\(^{-1}\) integrated luminosity
Collected with single muon trigger

Dominant backgrounds:
- \(Z \rightarrow \tau\tau + \text{jets}\)
- top pairs
- multi-jet (QCD + W+jets)

Event selection:
- Single isolated muon
- Opposite sign \(\tau_{\text{had}}\)
- 1 loose b-tagged jet (\(\varepsilon \sim 71\%\))

\[ b\phi \rightarrow b\tau_\mu \tau_{\text{had}} \]

Complementary to \(\phi \rightarrow \tau\tau\) and \(b\phi \rightarrow bbb\)

\[
m_{\text{vis}} = \sqrt{(p_{\tau_1} + p_{\tau_2} + E_T)^2}
\]
Searches in tau final states

Train NNs to discriminate against top and multi-jet backgrounds

NN b-tagger suppresses Z+jets background

Combine all NNs into single discriminant

Final discriminant = geometric mean of 3 NN outputs
$b\phi \rightarrow b\tau_\mu \tau_{\text{had}}$ limits

4.3 fb$^{-1}$ preliminary results

Limits set using “CLs” method

Most stringent limit at low $M_A$
Searches with b-quarks

New result with 5.2fb⁻¹ data

Search for neutral Higgs bosons in the multi-b-jet topology in 5.2 fb⁻¹ of p̄p collisions at \( \sqrt{s} = 1.96 \) TeV


Major improvements since previous 1fb⁻¹ publication

5x more data

Extended mass range: 90-300 GeV

Larger MC samples

Expanded and improved treatment of systematics

- e.g. b-tagging

Re-analyzed old 1fb⁻¹ data set

Fermilab-Pub-10-446-E


Major improvements since previous 1fb⁻¹ publication

5x more data

Extended mass range: 90-300 GeV

Larger MC samples

Expanded and improved treatment of systematics

- e.g. b-tagging

Re-analyzed old 1fb⁻¹ data set


Major improvements since previous 1fb⁻¹ publication

5x more data

Extended mass range: 90-300 GeV

Larger MC samples

Expanded and improved treatment of systematics

- e.g. b-tagging

Re-analyzed old 1fb⁻¹ data set


Major improvements since previous 1fb⁻¹ publication

5x more data

Extended mass range: 90-300 GeV

Larger MC samples

Expanded and improved treatment of systematics

- e.g. b-tagging

Re-analyzed old 1fb⁻¹ data set

Searches with b-quarks

5.2fb-1 collected with jet triggers – making use of lifetime information

3 or 4 jets, 3 must be b-tagged

Kinematic likelihood (D) used to select best jet pairing, + cut to suppress background

Very large multi-jet background

Challenging to model → data driven method

Multijet cross sections not well predicted → float normalisation
Background Modelling

2D correction: likelihood vs invariant mass

\[ S_{3\text{Tag}}^{\text{exp}}(D, M_{bb}) = \frac{S_{3\text{Tag}}^{\text{MC}}(D, M_{bb})}{S_{2\text{Tag}}^{\text{MC}}(D, M_{bb})} \cdot S_{2\text{Tag}}^{\text{data}}(D, M_{bb}) \]

3 b-tag background
MC correction factor
2 b-tag data

Predict background shape from 2-tagged data with correction from MC

MC composition extracted from fit to data

Validate model in sideband

21/03/2011
Jonathan Hays
Mass distributions

Di-jet invariant mass distribution used as input for the limit setting

DØ, 5.2 fb⁻¹

a) 3 jet
Low-mass likelihood

- DØ Data
- Background
- Heavy flavor

b) 3 jet
High-mass likelihood

- DØ Data
- Background
- Heavy flavor

D > 0.65, background normalised to data

21/03/2011
Jonathan Hays
Results

DØ, 5.2 fb$^{-1}$

Cross section × Br 95% C.L. [pb]

- Expected
- Expected ±1 s.d.
- Expected ±2 s.d.
- Observed

$M_A$ [GeV]

21/03/2011

Jonathan Hays
Select events with 3 b-tagged high pt jets

Form invariant mass of leading pair

Additional discriminant based on secondary vertex masses
Results
Many other results

“hidden valley” in 4b final state

4th generation in H→WW

Fermiophobic higgs

Latest results and updates:

http://www-cdf.fnal.gov/physics/new/hdg/Results.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
Conclusions

Rich programme of Higgs searches SM and BSM

Full data set + analysis improvements means possible exclusion $M_H < 190$ GeV

Updates and full combination expected this Summer

Sensitivity to BSM physics! Still some excitement left in the last days of Tevatron
BACKUP
Introduction

• In a conference talk it is not possible to discuss our analysis in depth. This talk is meant to clarify some of the details that feed into the calculation of the Tevatron Higgs limits.

• The Tevatron Higgs mass exclusion range is by its nature a probabilistic statement. All uncertainties must be treated properly, accounting for correlations, in order to obtain an accurate result.

• We choose theoretical inputs for our Higgs search limits that represent the consensus of the theoretical community. Picking extreme choices for these inputs would be biased and lead to over-coverage.

Derived from talk presented by M. Buehler at La Thuile 2011
Scale Variations ($\mu_R$ & $\mu_F$)

- Is our treatment of assessing cross section uncertainties due to scale variations reasonable?

- We obtain our gluon fusion production cross sections from:

- We use a scale variation of a factor of 2 from the central value ($\mu=m_H/2$) to estimate the magnitude of potential contributions from higher-order processes.

- The authors confirmed that higher order corrections to these cross sections are small and that the standard $\kappa=2$ scale variations are perfectly reasonable for assigning uncertainties.

- Another recent, independent publication argues for even smaller scale uncertainties than those being currently assigned in our searches:

- Yes, our treatment is sufficient and supported by the theoretical community.
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:

  [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.
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)
PDF Sets

Tevatron Jet Cross Sections

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
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 $1\sigma$. 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.

- We are not underestimating our uncertainties.
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
Conclusion

• Our Higgs limits are based on standard practices of the HEP community and the base assumptions that meet a consensus

• We are happy that our results on Higgs boson searches have captured the interest of the HEP theory community

• We welcome the scrutiny that comes with producing such important results

• The Higgs limits obtained by the Tevatron are sound and indicate exclusion of the Higgs boson with masses between 158 and 175 GeV at the 95% CL