# $H \rightarrow WW$ searches at the Tevatron

Davide Gerbaudo
Princeton University

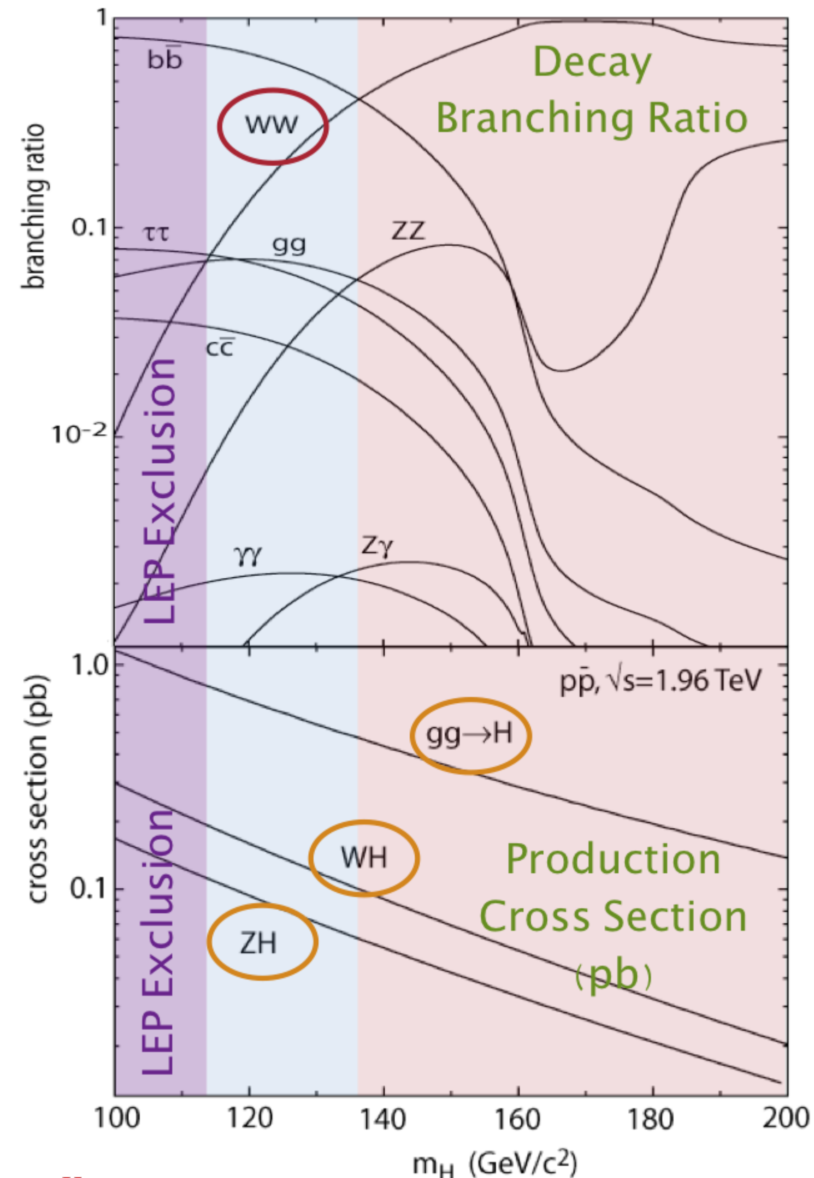
BNL Higgs workshop
May 3rd, 2011

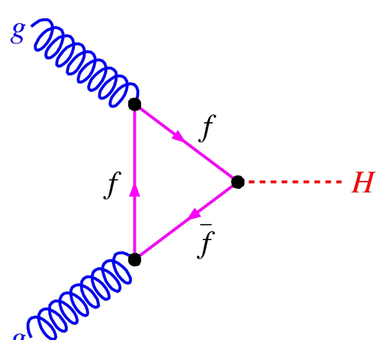
**On behalf of the CDF and DØ Collaborations**

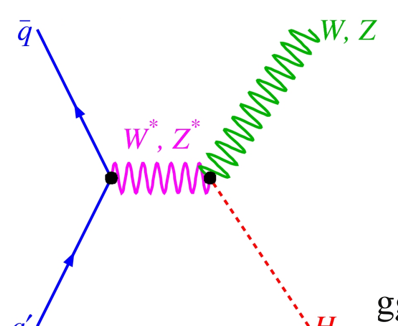
# High-mass Higgs searches at the Tevatron

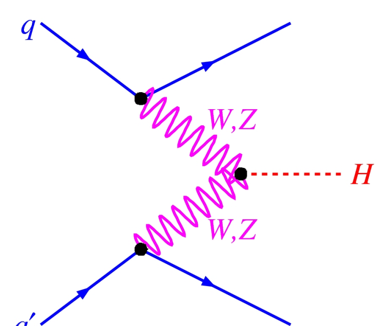
- Higgs production cross section for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$TeV
  - Gluon fusion (ggH): $\sigma \approx 0.2$–1pb
  - Associated production (VH): $\sigma \approx 0.01$–0.3pb
  - Vector boson fusion (VBF) $\sigma \approx 0.01$–0.1pb
- Precision EWK data indicates $114 < m_H < 186$GeV @ 95 C.L.

- $H \rightarrow WW$ is the main decay mode for $m_H > 135$GeV, characterizing (most of) high-mass searches.



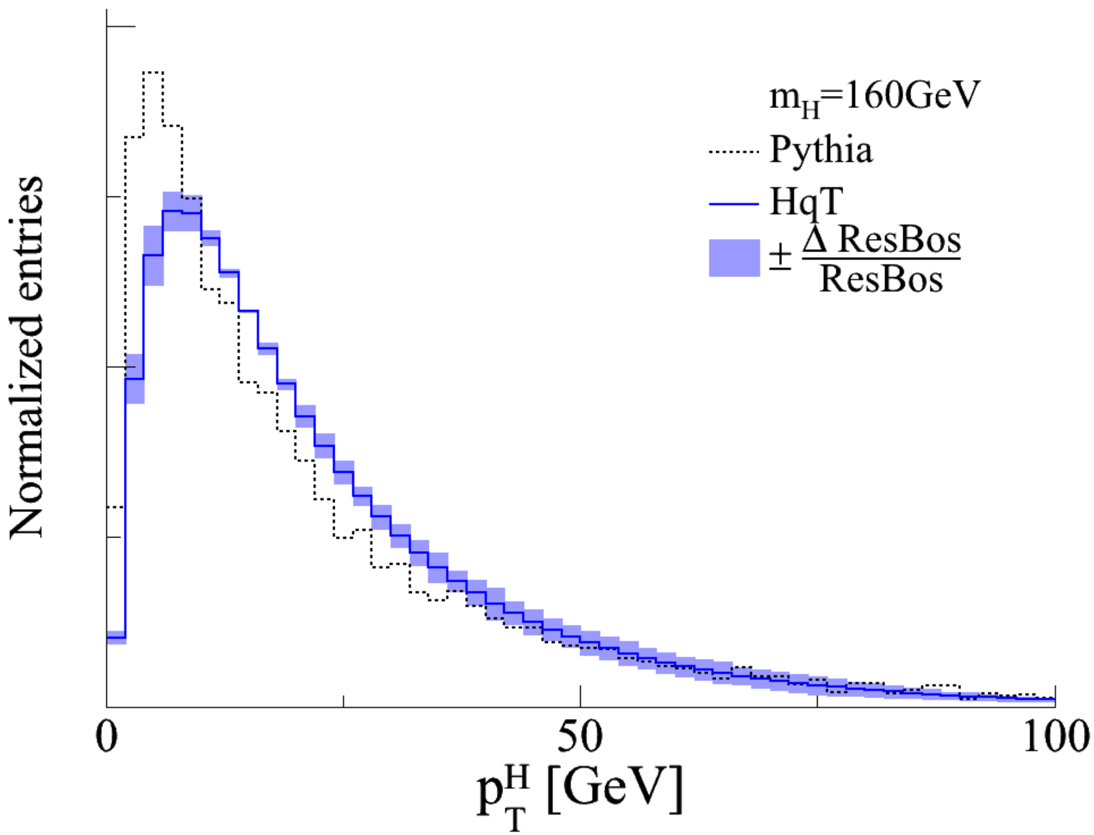



# Production cross section

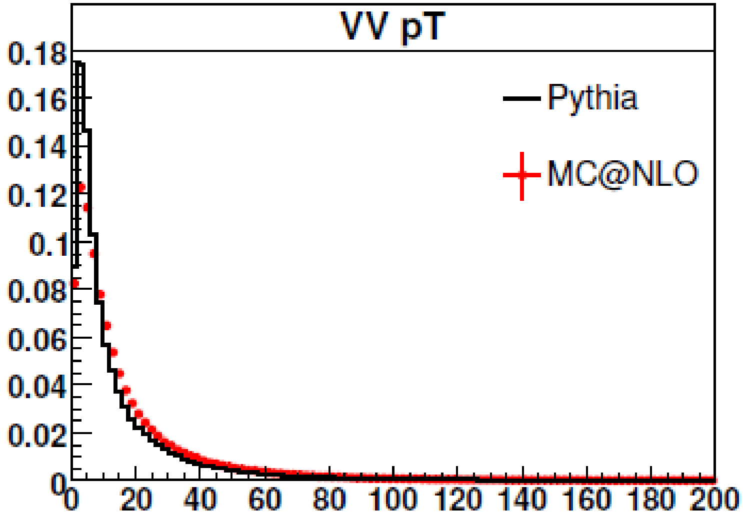
• Our signal samples are generated (LO) with Pythia6
•We adjust the yield and the main kinematic distributions ($p_T^H$) to the latest calculation available:
• $gg \rightarrow H$
  • NNLO+NNLL cross section from JHEP **0904**, 003 (Anastasiou et al, 2009) and Phys Lett B **674**, 291 (de Florian et al, 2010)
  • computed with MSTW08 PDF set
  • $p_T^H$ reweighted to NNLL+NLO from HqT, with relative uncertainty from ResBos
• VH: NNLO from JHEP **1010**, 064 (Baglio et al., 2010)
• VBF: NNLO from Phys Rev Lett **105**, 011801 (Bolzoni et al, 2010)

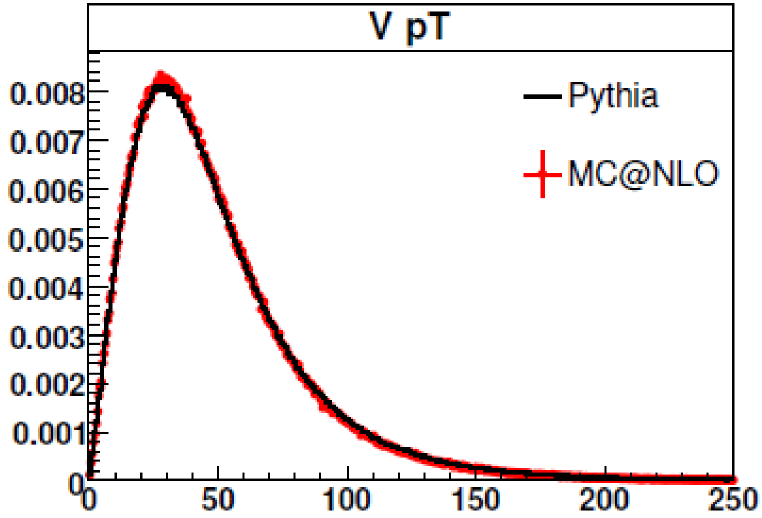


# Backgrounds

We apply few adjustments to the backgrounds as well. We use what was learnt in other analyses to improve the modeling of some background variables:

- W, Z + jets: boson pT reweighted to match the spectrum observed in data, after unfolding
- diboson VV: 2D reweigthing as a function of $p_T(VV)$ and $p_T(V)$ to match the prediction from MC@NLO

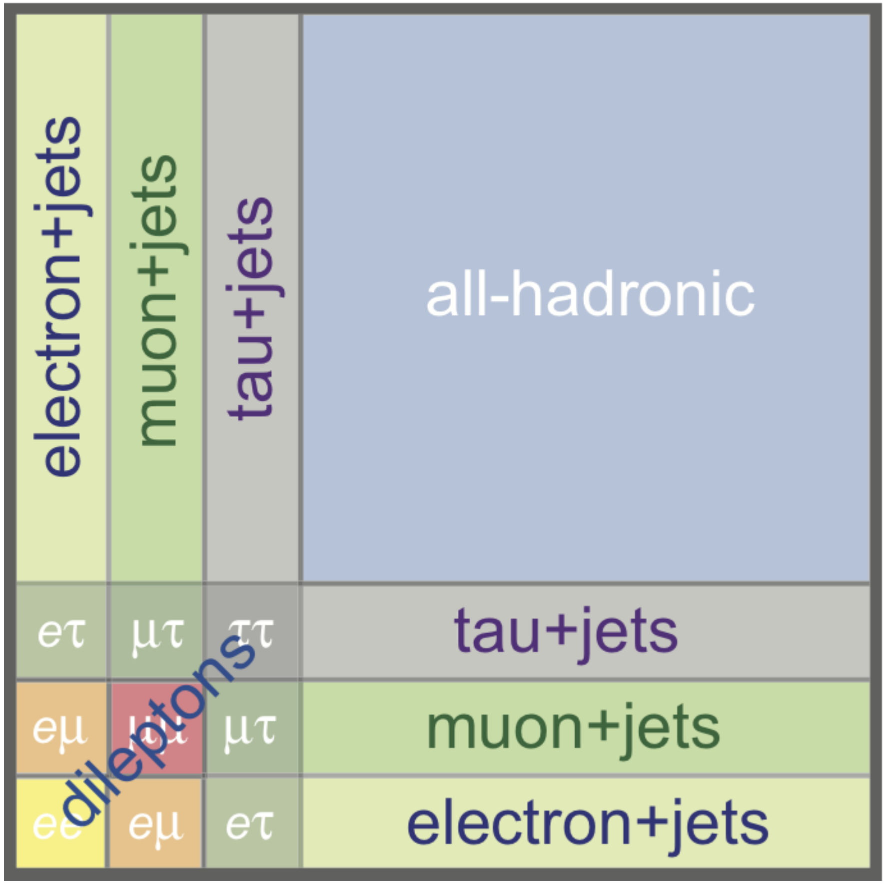


# H→WW final states

Higgs branching fractions computed with HDECAY

WW decays:




Purely leptonic WW decay provides the final state with the best sensitivity, but it's not enough and it's not the only one...

- A cut-based analysis alone is not sufficient → use multivariate techniques
- Use of all feasible final states, with at least one leptonic W decay

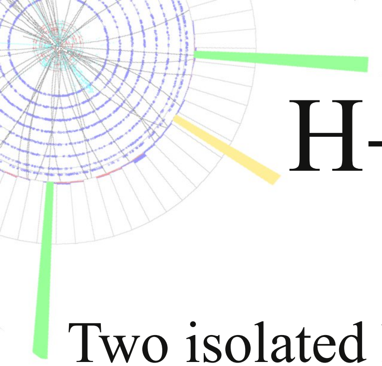
Divide and conquer!

- Split the dataset in several reconstructed final states
- Different kinematic and topology
- Optimize the MVA for different mixtures of signal and background contributions

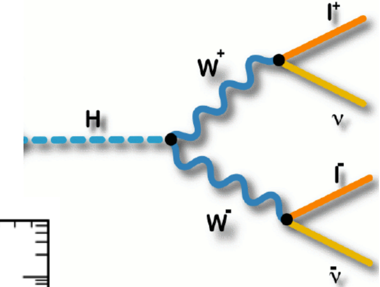
# Winter update

• Both experiments increased the dataset being analyzed: most sensitive channels with 7.1/fb for CDF and 8.1/fb for DØ
• Expect to have 10/fb by the end of the Tevatron RunII

| Channel | CDF | DØ |
|---|---|---|
| | **$H \to WW \to \ell^+ \nu \ell^- \nu$** | |
| $\ell\ell$ +0/1/2$^+$ jet ($\ell$=e,$\mu$) | 7.1/fb | 8.1/fb |
| $\ell\ell$ +0/1 jet, low mass | 7.1/fb | – |
| $\tau_{had}\ \ell$ | 7.1/fb | 7.3/fb NEW! |
| $\tau_{had}\ \ell$ , 2$^+$ jets | – | 4.3/fb NEW! |
| | **$H \to WW \to \ell\ \nu\ qq$** | |
| $\ell\nu$ + 2$^+$ jet ($\ell$=e,$\mu$) | – | 5.4/fb |
| | **$VH \to VWW$** | |
| Same-sign dileptons | 7.1/fb | 5.4/fb |
| Trileptons | 7.1/fb | – |



# $H \to WW \to \ell^+ \nu \ell^- \nu$: pre-selection

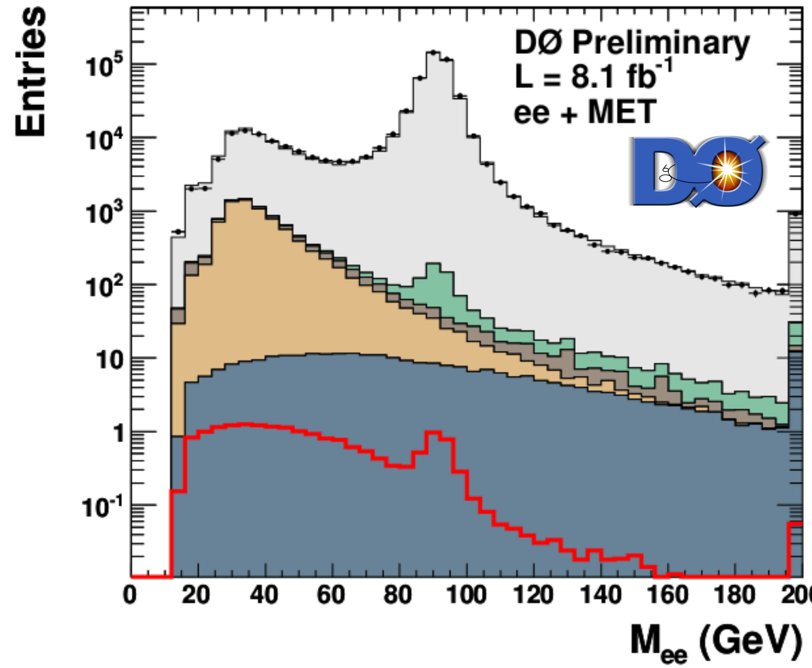


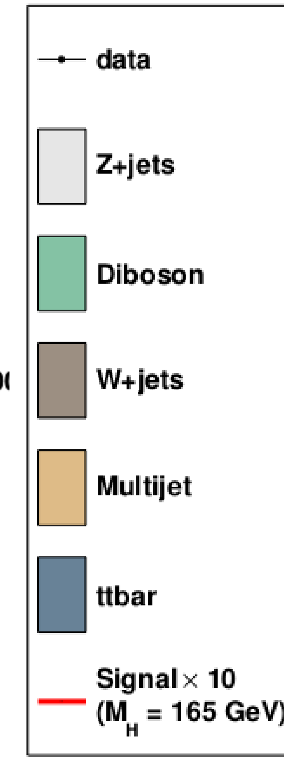

Two isolated high-$p_T$ leptons ($\ell$ = e, μ) with opposite charge.

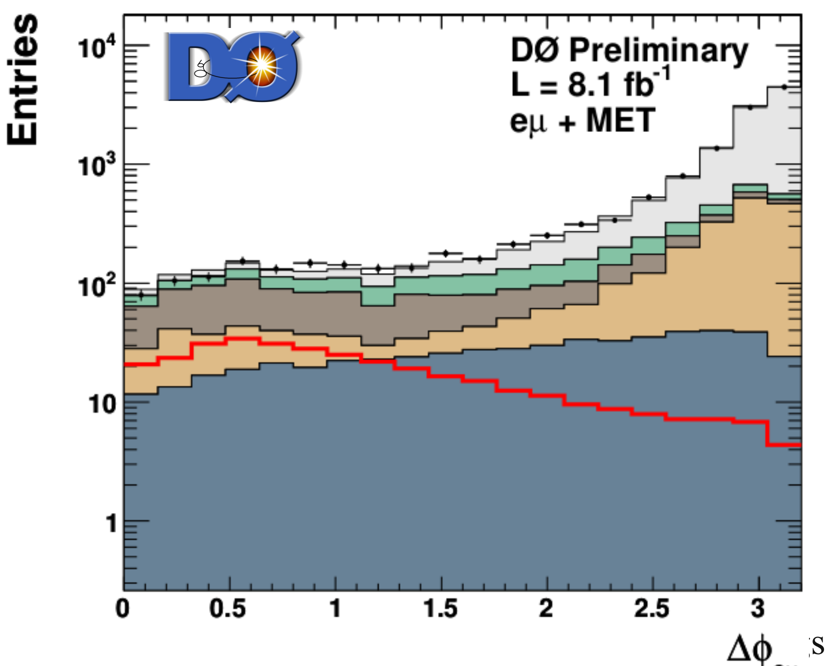
Each analysis is sub-divided in several sub-channels:

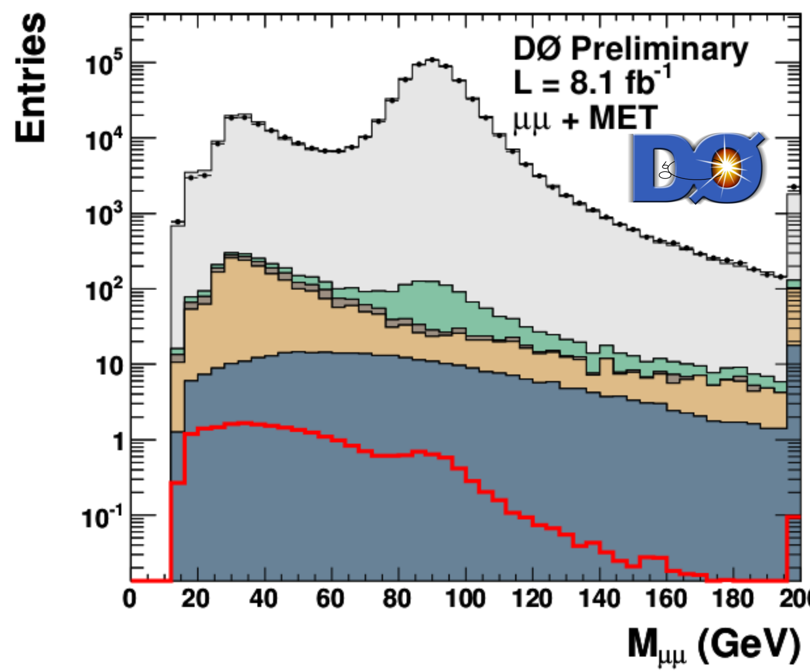
- DØ: ee, eμ, μμ
- CDF: low/high sensitivity or $M_{\ell\ell}$

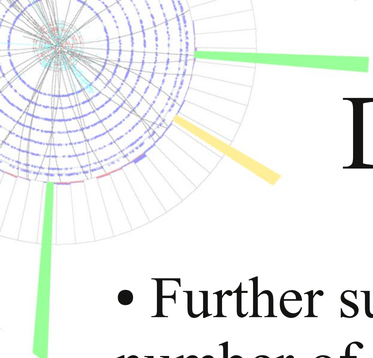
Different efficiencies, kinematics, and resolutions



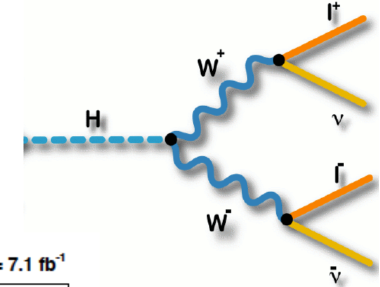



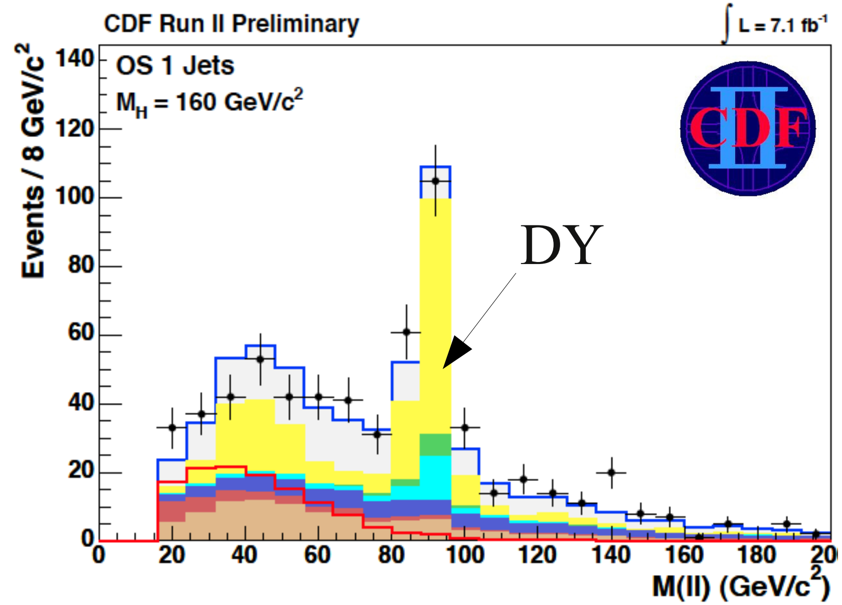





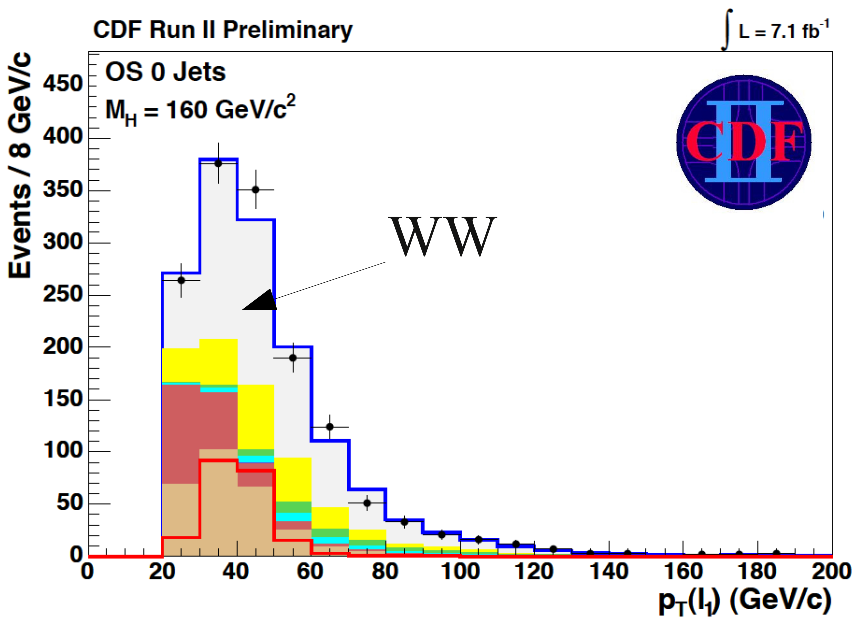
# Divide and conquer

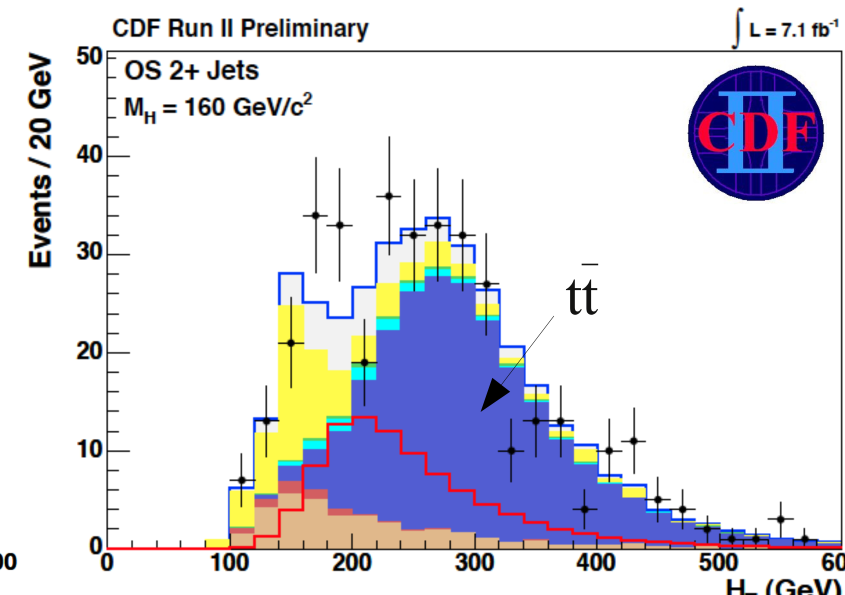


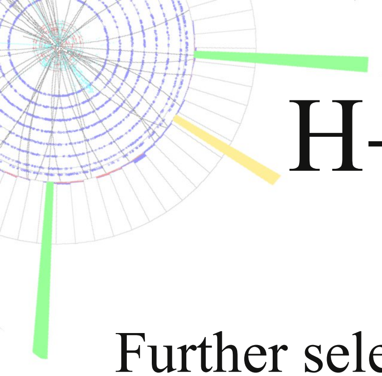

- Further subdivision based on the number of reconstructed jets
- Different signal and backgound compositions:
  - 0jet: WW
  - 1jet: $Z/\gamma^*$
  - $\geq$ 2jets: $t\bar{t}$
- train MVA separately in order to maximize sensitivity



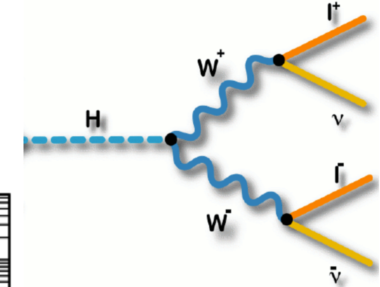




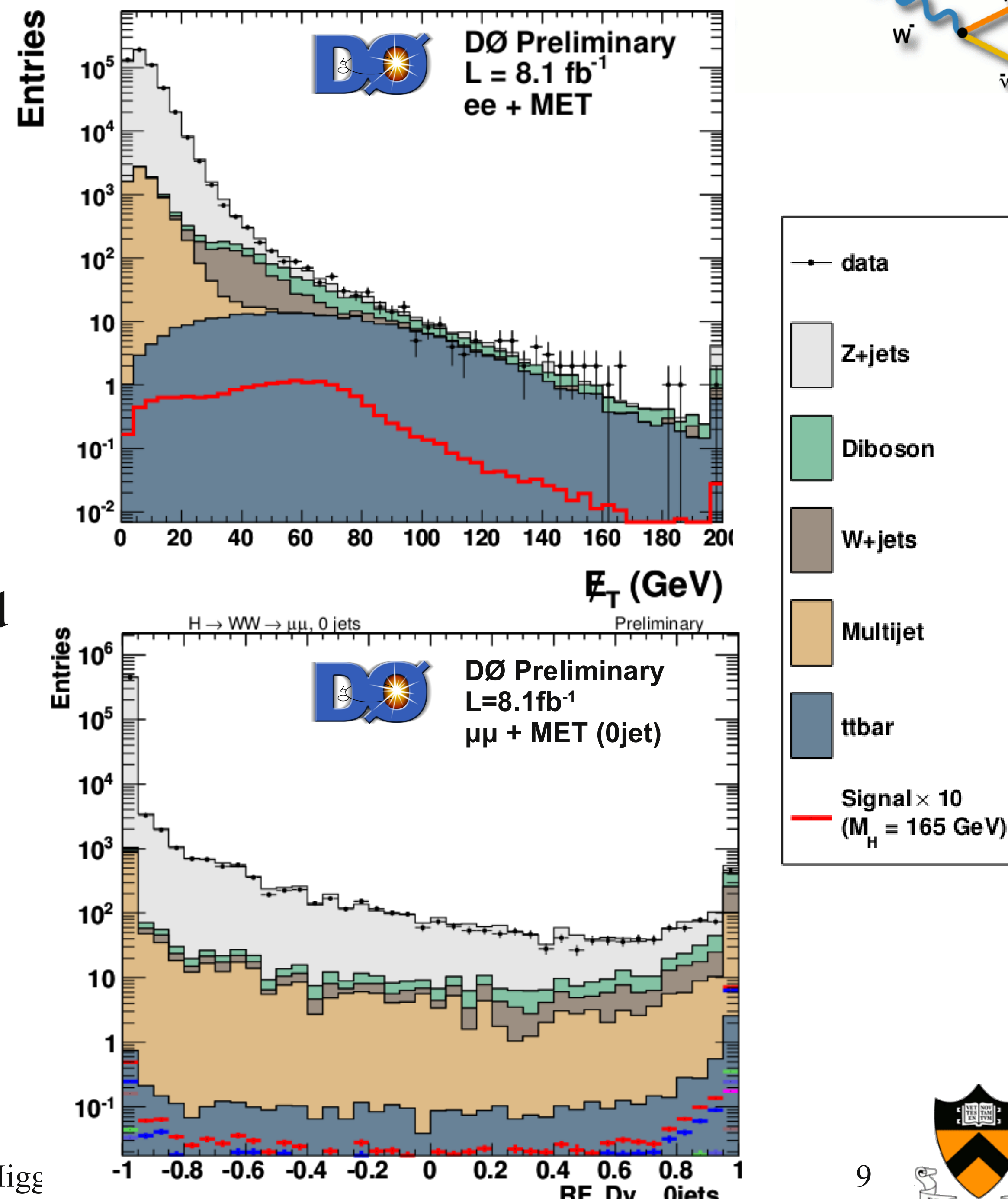


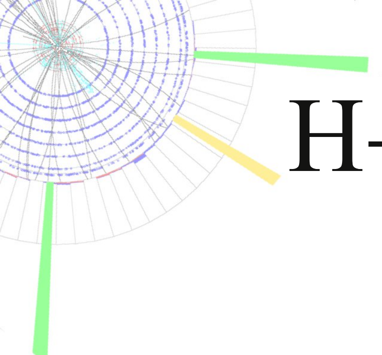
# H→WW→$\ell^+\nu\ell^-\nu$: final selection



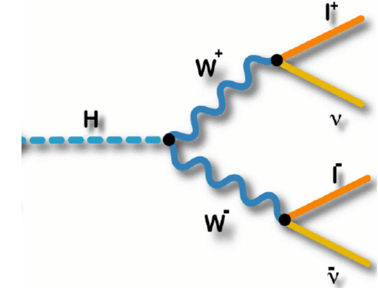

Further selection criteria are applied to reduce the largest background (Z/γ*)

- CDF
  - require high missing $E_T$
- DØ
  - ee, μμ train DT against Z/γ*, then require high DT output
  - eμ kinematic selection ($E_T$ and $M_T$)
  - jet splitting and Z/γ* DT improved DØ expected sensitivity by 15-30%
- Expect ~ 100 signal events at final selection for CDF + DØ @165GeV



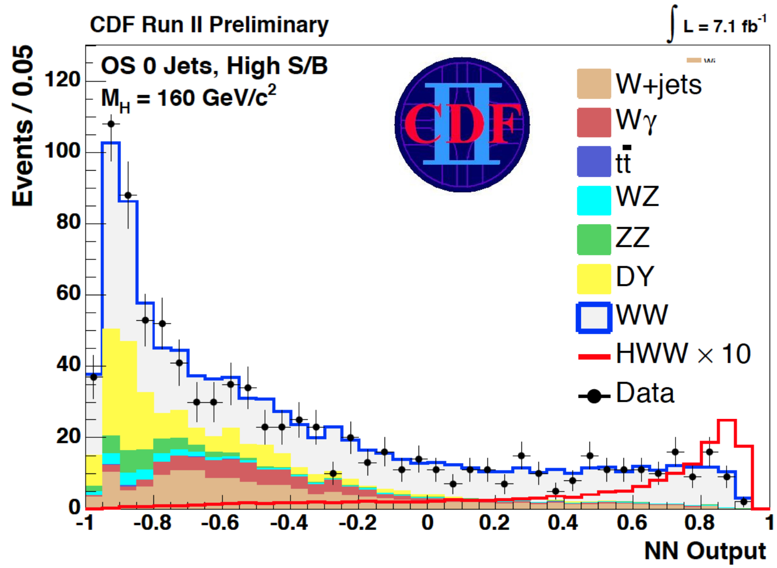


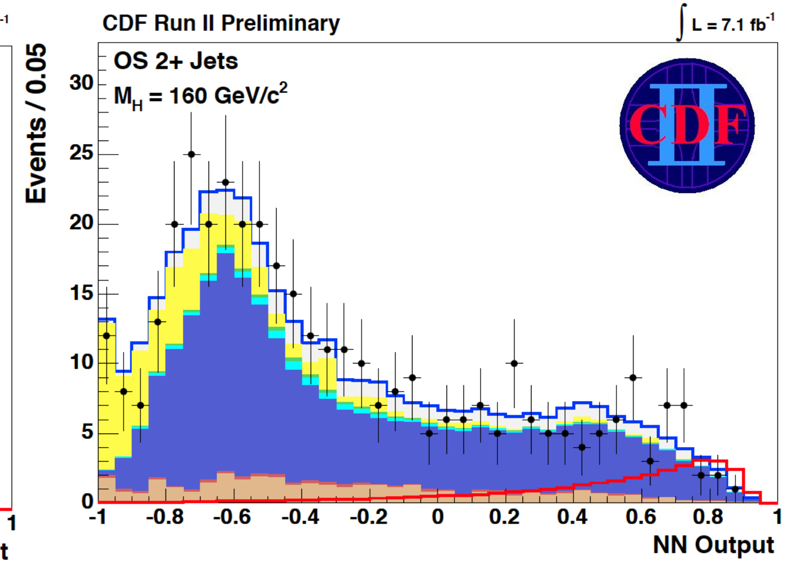
# H→WW→$\ell^+\nu\ell^-\nu$: final MVA

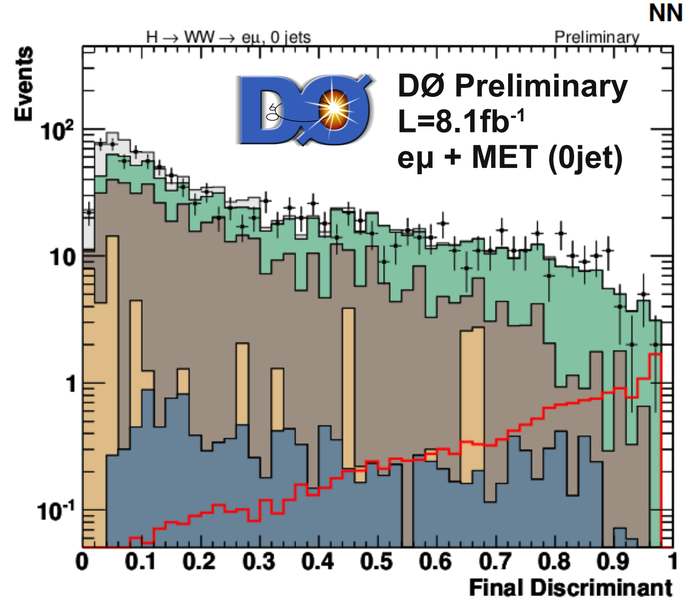


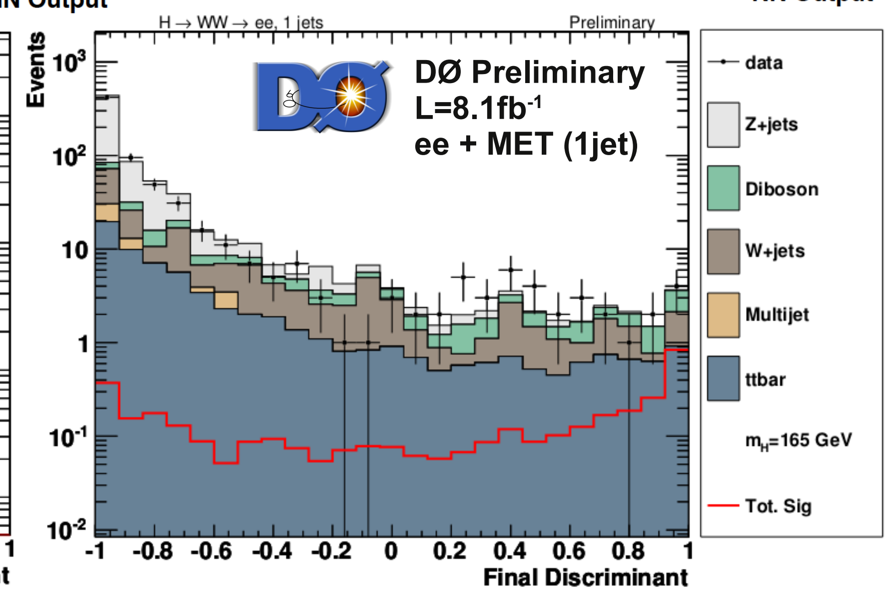

At each mass point, trained separately for each sub-sample.
- CDF: Neural Net
- DØ : Decision Tree

Input variables:
- kinematic
- topological
- CDF: matrix element likelihood ratio
- b-tag as an input or as a veto



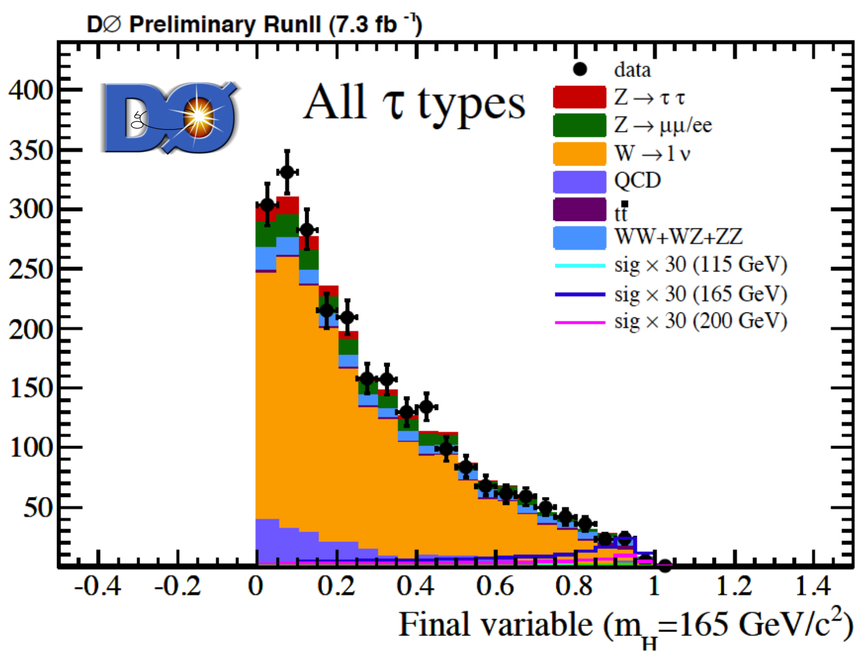



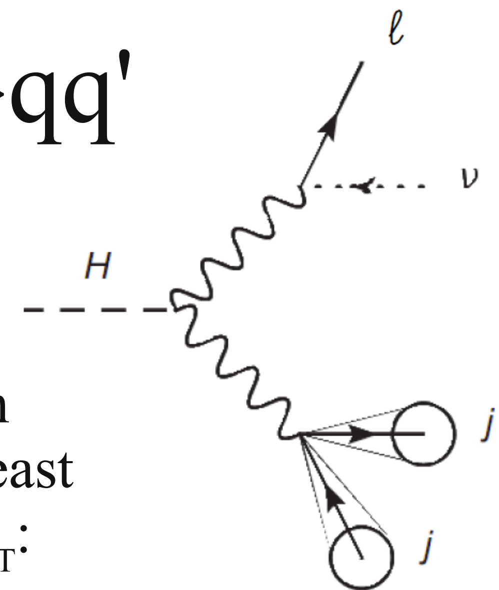
# Other decays: $W \to \tau\nu$ and $W \to qq'$

Selecting events with one lepton (e,μ), and one hadronic τ:

- CDF analyses updated: 7.1/fb
- DØ new analyses:
  - $\mu\tau_{had}$ + ≤1jet (7.3/fb)
  - $e(\mu)\tau_{had}$ +≥2jets (4.3/fb)

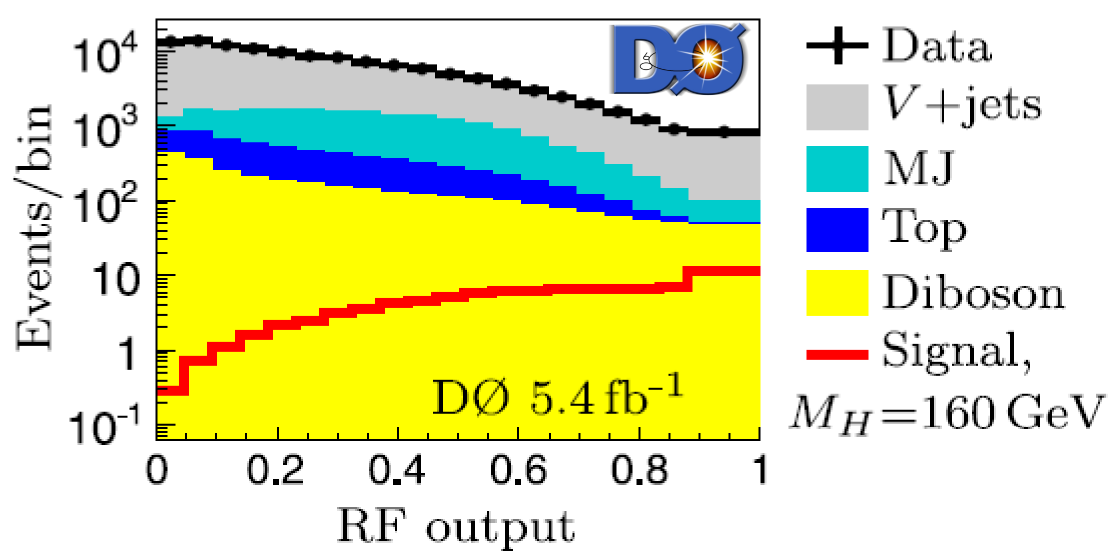


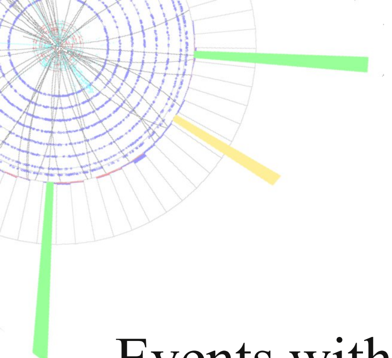

$H \to WW \to \ell\nu jj$:



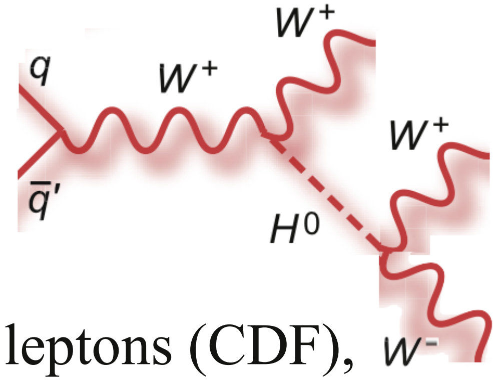

Selecting events with one lepton (e,μ), at least 2 jets, and missing $E_T$:

- DØ recent publication (5.4/fb): Phys. Rev. Lett. 106, 171802 (2011)
- Sensitivity: 5×SM @ $m_H$=160GeV





# VH → VWW




Events with two same-sign leptons and missing $E_T$ (CDF and DØ):

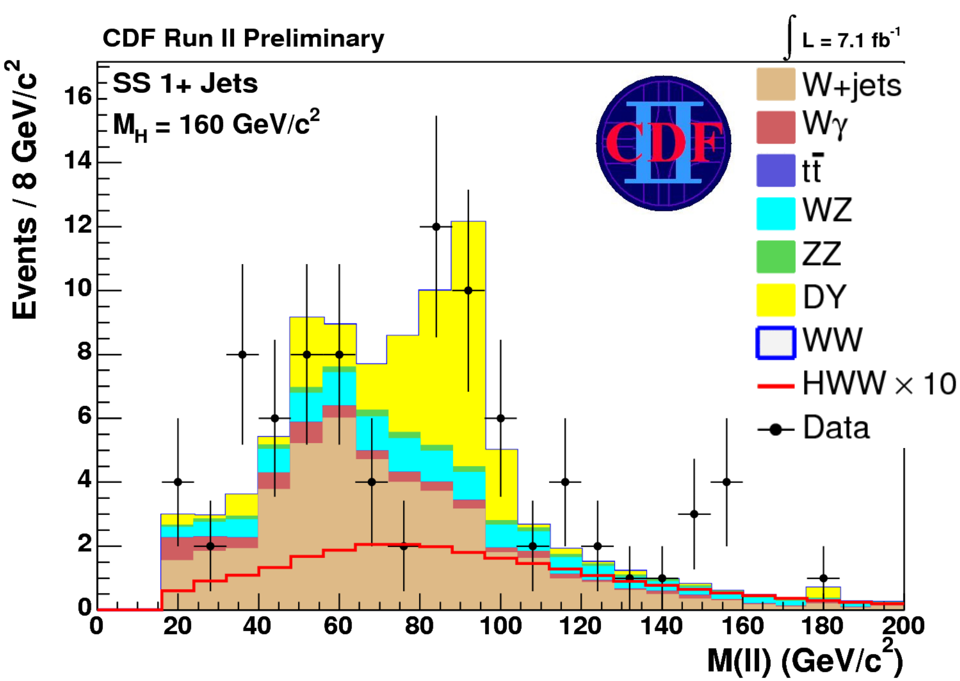
• Different signal contributions: WH → WWW

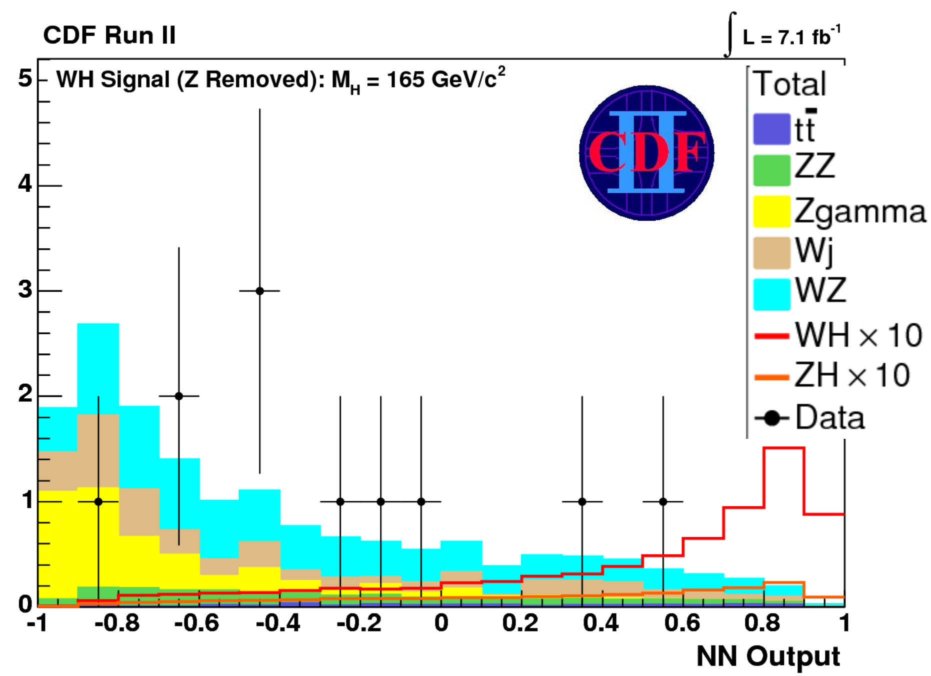
• Different backgrounds: W+jets, DY with charge flips

Events with three leptons (CDF), subdivided in three channels:

• inside Z-peak (same flavor, opposite sign) with one or two jets

• outside Z-peak



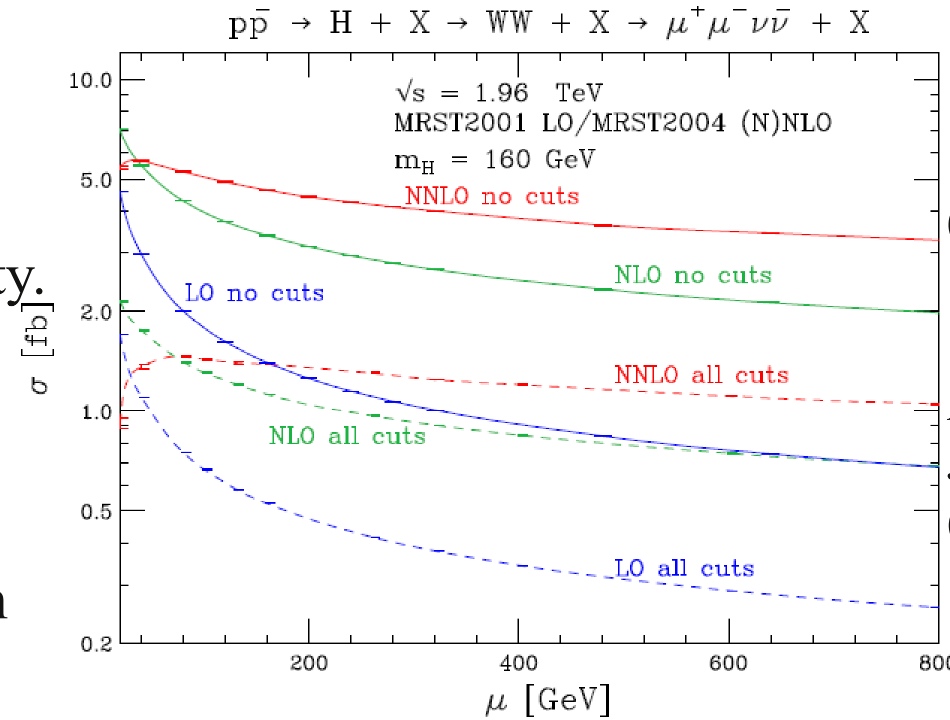



# Systematic uncertainties

Uncertainty on σ(gg→H) normalization assessed separately for each jet multiplicity.
- scale variation: 7-33%
- PDF following PDF4LHC prescription: 8-30%

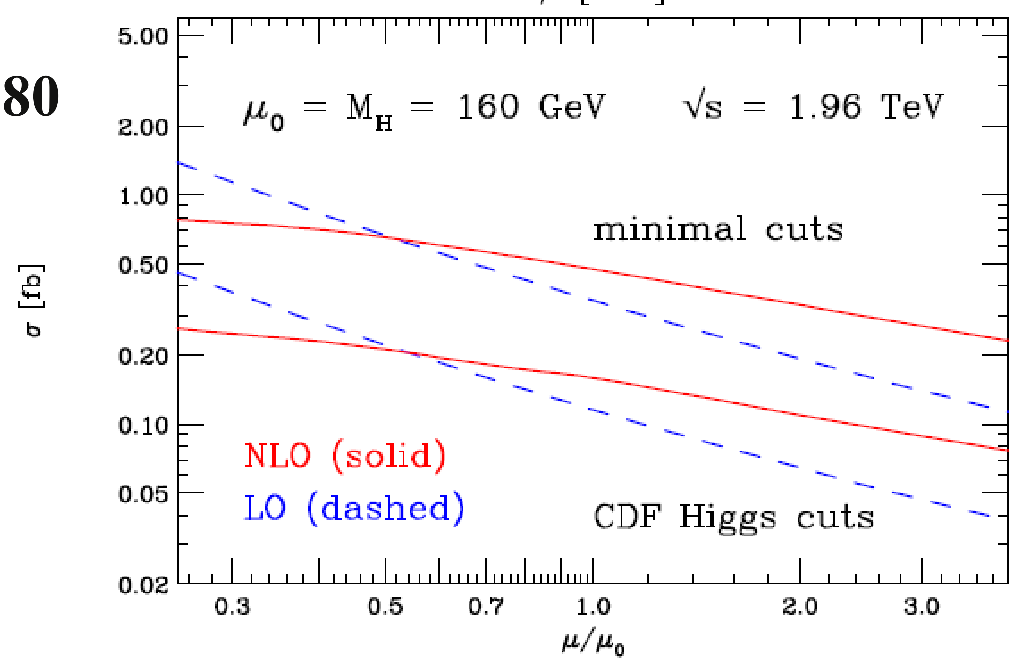
Shape $p_T^H$: ResBos $\mu/\mu_0$ variation

Backgrounds:
- $\sigma(t\bar{t})$: 10% from Phys Rev D **80** 054009 (Moch et al, 2009)
- WW/WZ/ZZ: ~7% by varying μ with MCFM
- remaining backgrounds and further details in hep-ex/1103.3233.




0jets: NNLO
1jets: NLO

Anastasiou et al, JHEP **0908**, 099 (2009).



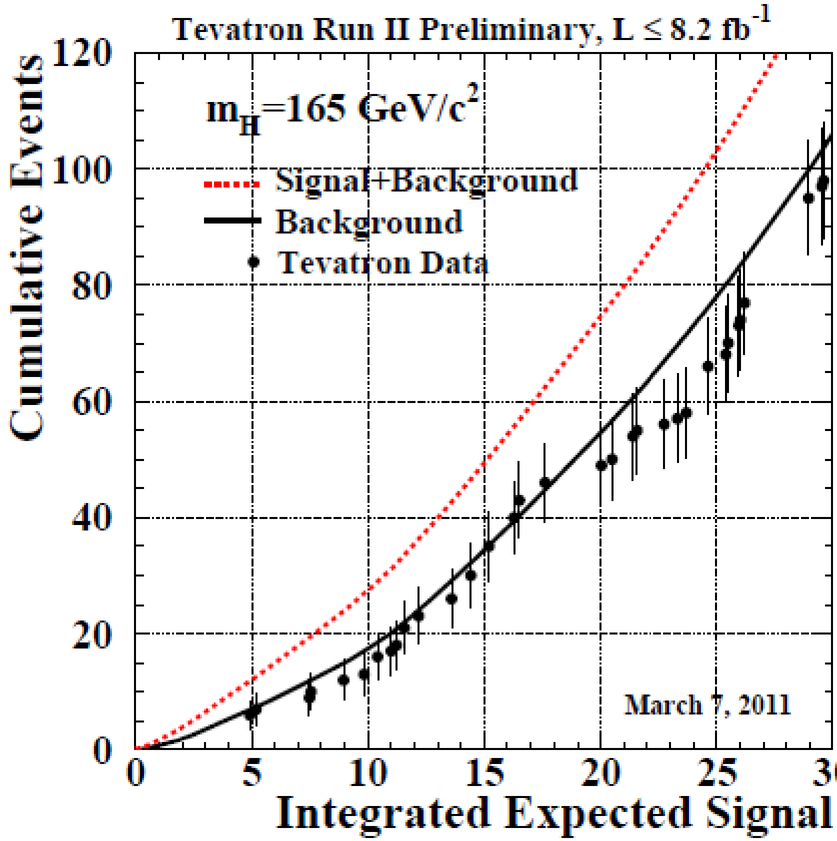

$2^+$jets: NLO

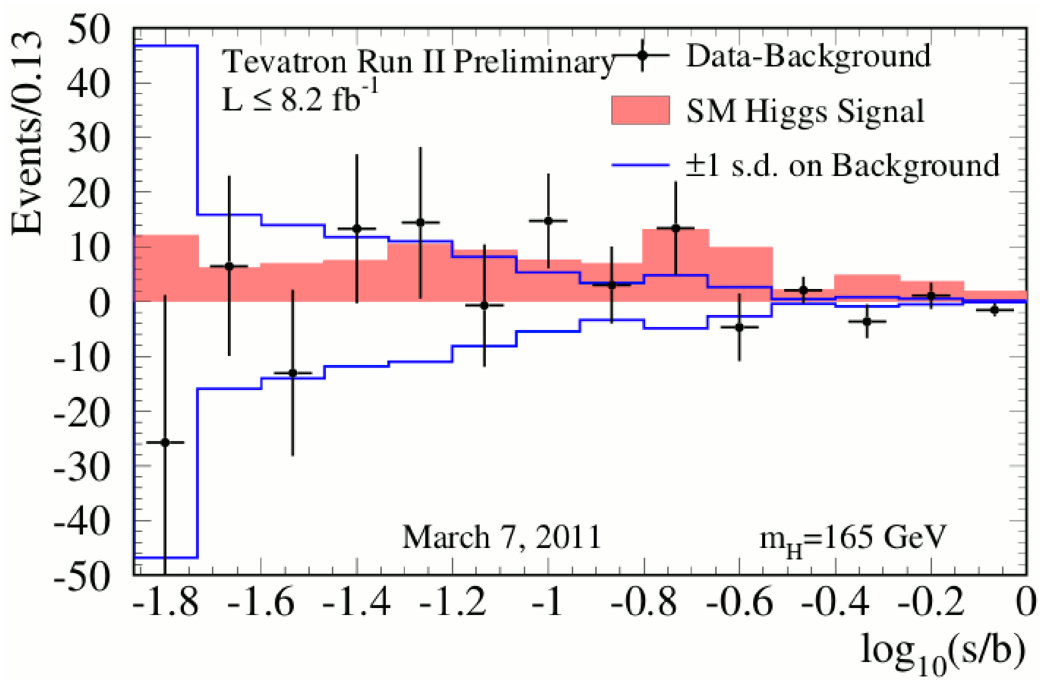
Campbell et al, Phys. Rev. **D81**, 074023 (2010).

# Systematic uncertainties

Gaussian prior assigned to each uncertainty;
nuisance parameters constrained from data
→ more details in Tom's talk on Friday

Other uncertainties (normalization and shape), uncorrelated among experiments and channels:
- lepton ID efficiencies
- jet energy scale and resolution, multijet background estimate
- b-tag efficiency
- detailed list in hep-ex/1103.3233.



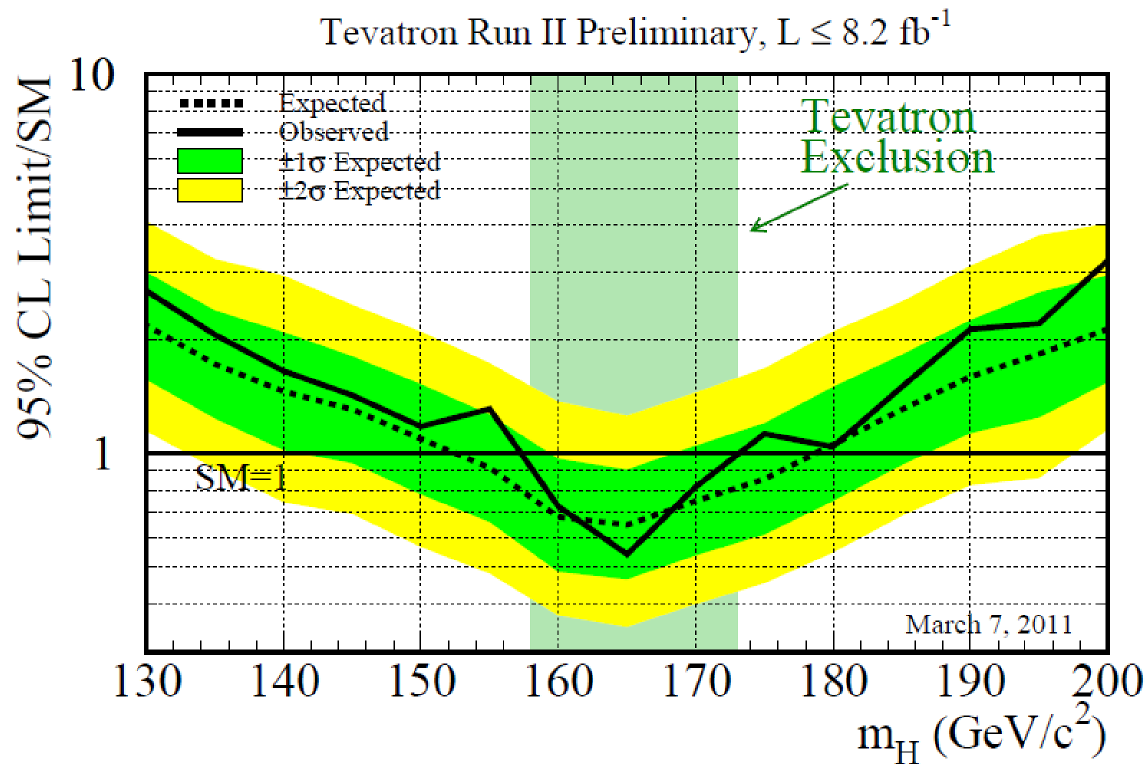




No significant excess observed.

Both experiments reach SM sentitivity for $m_H$ ~ 165GeV

# Limits and Conclusions

- Important milestone achieved by CDF and DØ, both reaching SM sensitivity in the H → WW channel
- Results achieved thanks to large datasets, advanced analysis techniques, and a divide-and-conquer approach
- This result would have not been possible without the most accurate theoretical predictions for signal production




Exclusion at 95% C.L. of SM Higgs hypothesis for $158<m_H<173$ GeV.

Thank you!

# Backup

# Expected limits per channel

Expected limit for mH=165GeV, times SM

| Channel | CDF | DØ |
|---|---|---|
| | **$H \rightarrow WW \rightarrow \ell^+ \nu \ell^- \nu$** | |
| $\ell\ell$ +0/1/2$^+$ jet ($\ell$=e,μ) | 0.93 | 0.97 |
| $\ell\ell$ +0/1 jet, low mass | included in 0.93 | – |
| $\tau_{had}$ $\ell$ | 13.1 | 7.5 |
| $\tau_{had}$ $\ell$ , 2$^+$ jets | – | 12.3 |
| | **$H \rightarrow WW \rightarrow \ell \nu qq$** | |
| $\ell\ell$ +0/1/2$^+$ jet ($\ell$=e,μ) | – | 5.1 |
| | **$VH \rightarrow VWW$** | |
| Same-sign dileptons | included in 0.93 | 7.0 |
| Trileptons | included in 0.93 | – |

# Matrix element discriminant

The probability density for any given mode m

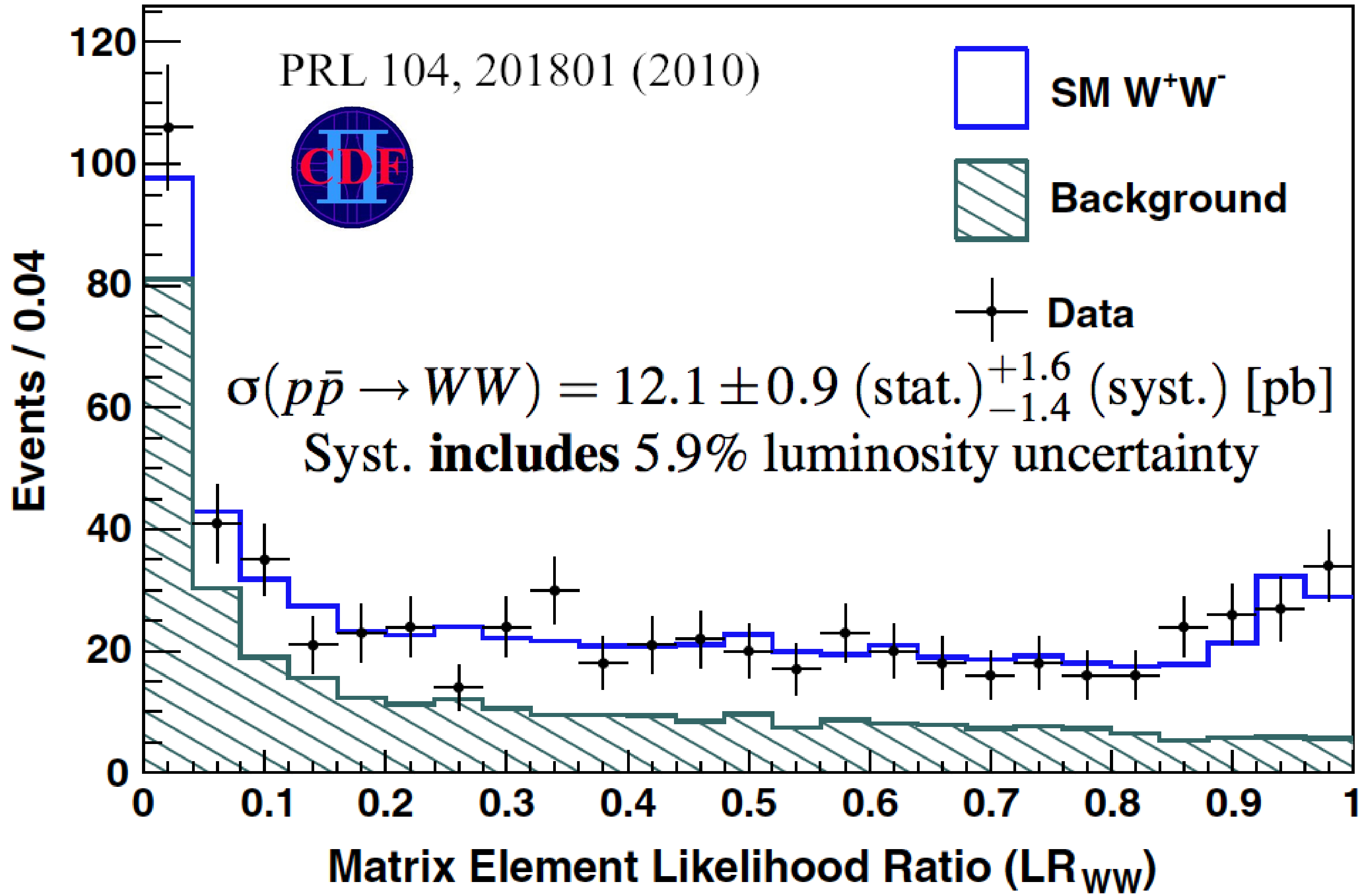
$$P_m(x_{obs}) = \frac{1}{<\sigma_m>} \int \frac{d\sigma_m^{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

| | |
|---|---|
| $x_{obs}$ | are the observed "leptons" and $\vec{\not{E}}_T$, |
| $y$ | are the true lepton four-vectors (including neutrinos), |
| $\sigma_m^{th}$ | 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:

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

# MVA cross check



# Response 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**

M. Buehler o.b.o TEVNPHWG La Thuille 2011 4

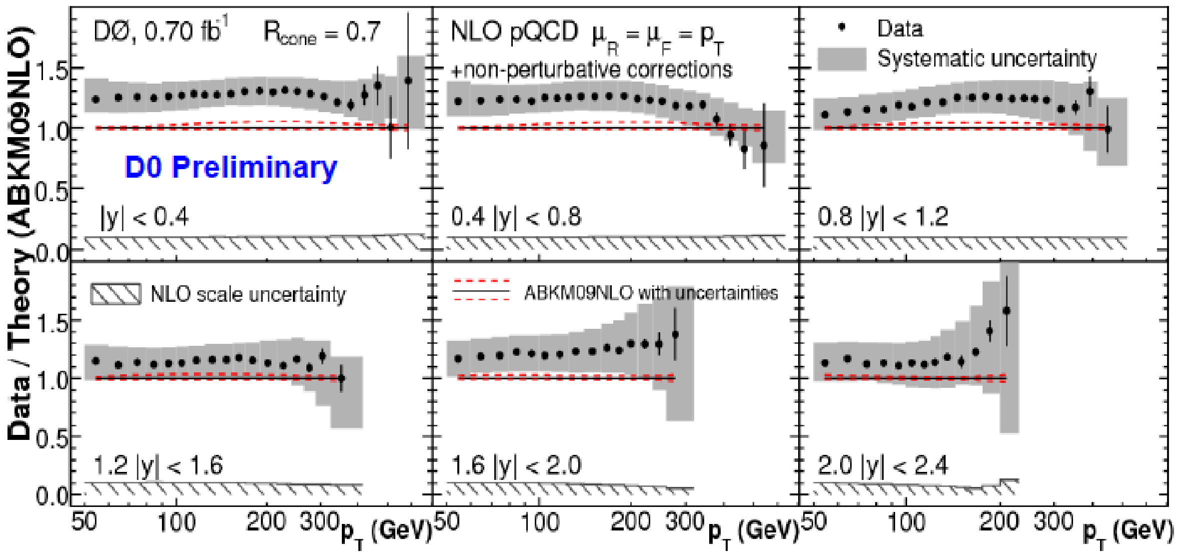
# Response II

## 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)

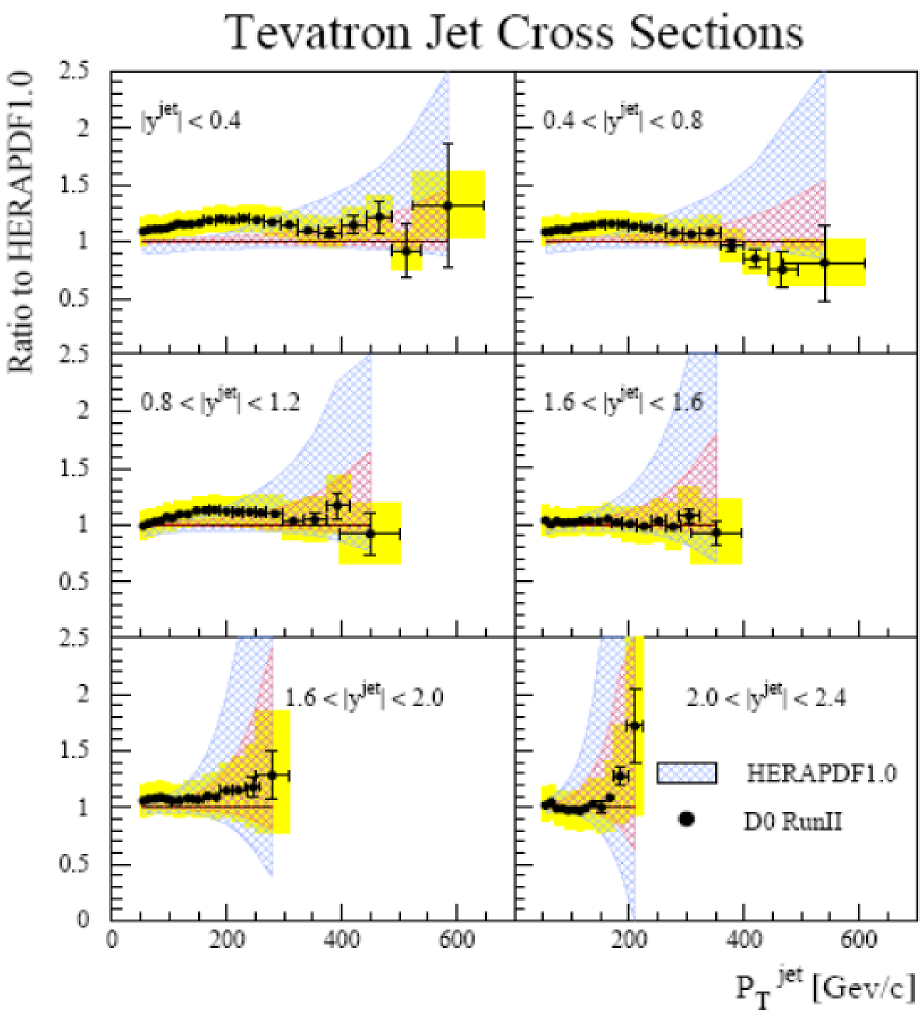
(→ Uncertainty on ABKM Prediction)




M. Buehler o.b.o TEVNPHWG La Thuille 2011 5

# Response 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

M. Buehler o.b.o TEVNPHWG La Thuille 2011

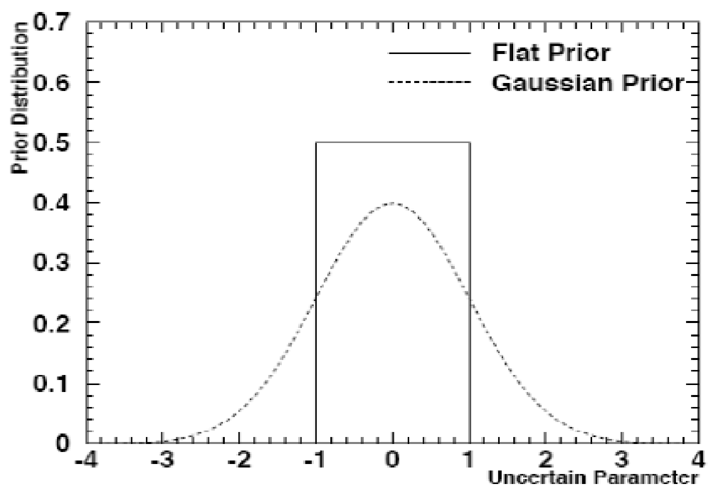
# Response IV

## 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**




7

# Response 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

M. Buehler o.b.o TEVNPHWG La Thuille 2011 8