

# Prospects from the Tevatron

International Workshop on the  
Interconnection Between  
Particle Physics and Cosmology

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Frank Chlebana, Fermilab

# Outline

*What factors influence the ultimate potential of the Tevatron*

- *The Tevatron, CDF, and DØ*

Tevatron performance

Detector upgrades

Trigger and Data Acquisition

- *Some Example Analyses*

The  $M_W - M_{\text{Top}} - M_{\text{Higgs}}$  relationship

Understanding backgrounds

Uncertainties on the Parton Density Functions

Searches for FCNC

Searches for Higgs

*Trying to illustrate concepts*

*Tend to pick examples from CDF since I am more familiar with CDF...*



The Fermilab accelerator complex accelerates protons and antiproton to 980 GeV

Produces collisions with a center of mass energy of 1.96 TeV

*Worlds highest energy particle collider*

*Able to probe distances scales  $\sim 10^{-17}$  cm*

CDF and DØ detectors used to study the results of the collisions

**Run I (1992 - 1996)**

$\sqrt{s} = 1.8$  TeV  
 $6 \times 6$  bunches ( $3 \mu\text{s}$  spacing)  
 $3 \times 10^5$  crossings/s  
 $\mathcal{L}^{\text{inst}} = 1.89 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$   
 Delivered about  $140 \text{ pb}^{-1}$

**Run II (2001 - ?)**

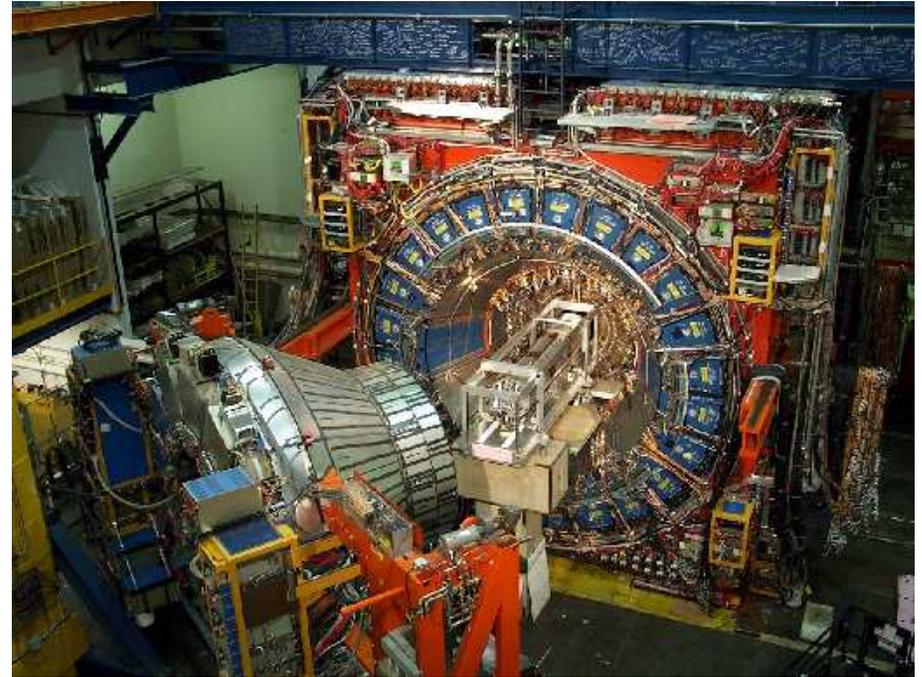
$\sqrt{s} = 1.96$  TeV  
 $36 \times 36$  bunches ( $396 \text{ ns}$  spacing)  
 $25 \times 10^5$  crossings/s  
 $\mathcal{L}^{\text{inst}} = 30 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$   
 Expect  $4 - 8 \text{ fb}^{-1}$   $\sim 30-60 \times \text{Run I}$

Number of Events = Luminosity  $\times$  Cross Section

## The DØ Collaboration



## The CDF Detector



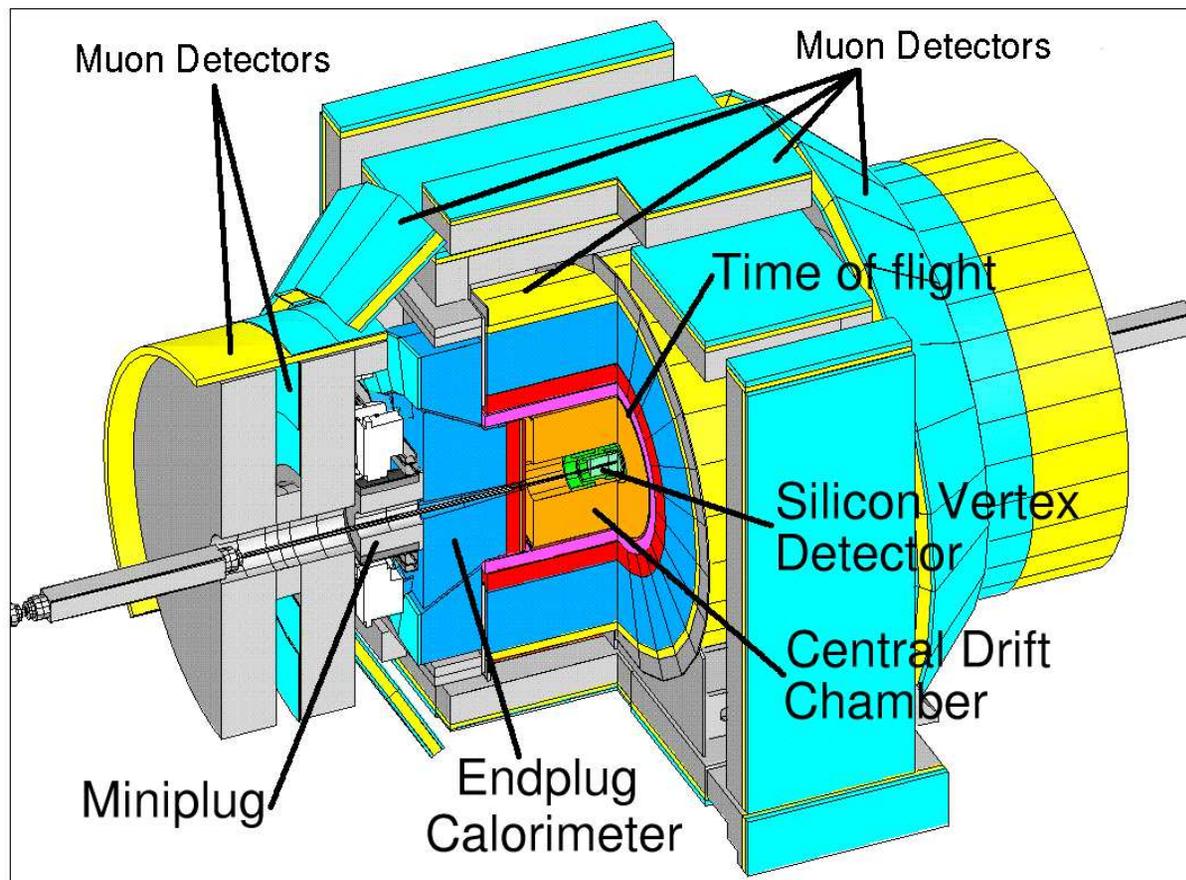
The CDF and DØ multinational collaborations include *hundreds of physicists* from many institutions around the world

Detector components built at locations around the world and integrated together at Fermilab

*General purpose detectors*

→ *Allow for a broad and varied research program*

# CDF Detector Upgrades for Run II



Detector upgrades build on the experience from Run I

- *Better detectors*
- *Improved acceptance*
- *New triggering capabilities*

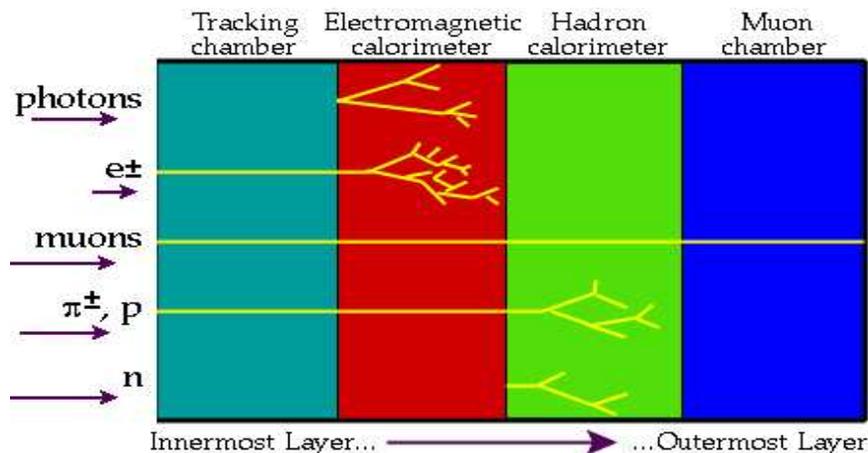
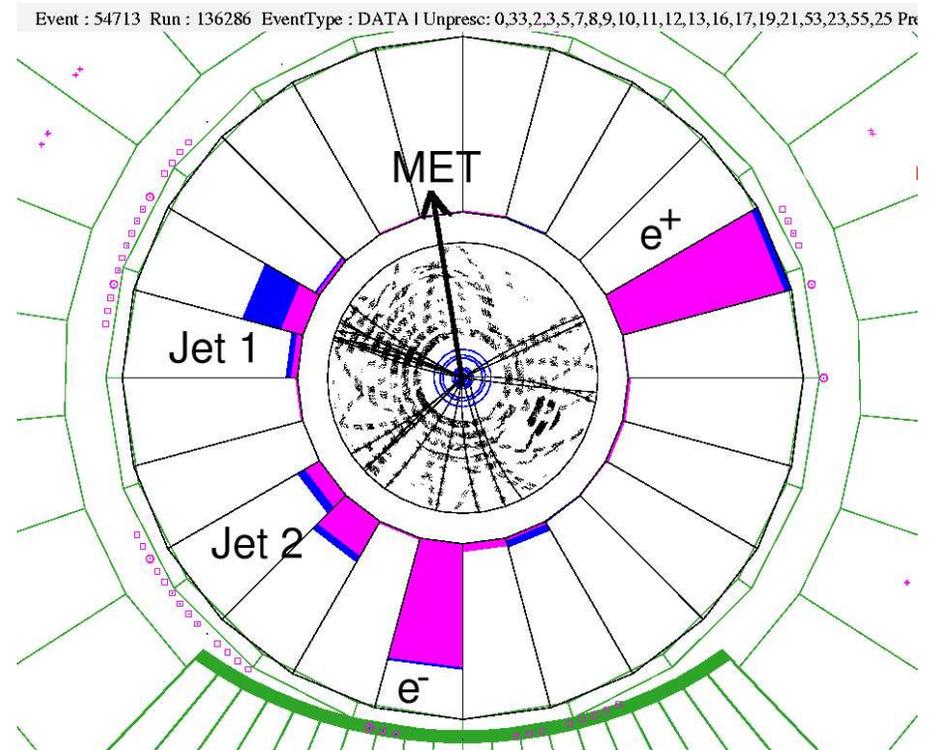
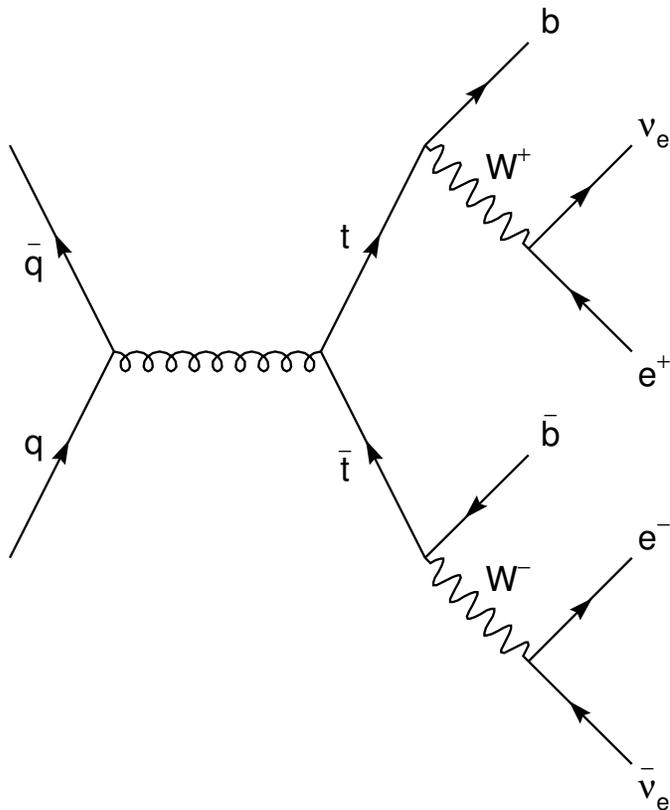
Need to cope with higher data rates and shorter beam crossing times

New physics has small cross sections and is swamped by standard physics background

Trigger needs to select small cross section processes from the *huge background*

*Essential to continually monitor data quality and quickly identify and repair faulty hardware (requires "experts" ...)*

# Signature Consistent With Top Production



Decay signature *Jets, electrons, muons, Missing  $E_T$*

- *Silicon tracking for identifying  $b$  jets (displaced vertex)*
- *XFT tracking trigger COT + Muon Chambers*
- *Calorimeter Jets and Missing  $E_T$*

# Trigger and Data Acquisition System

The online “trigger” reduces the **2.5 MHz** (396 ns crossing) beam crossing rate to **~ 100 Hz** in three stages

## L1 Trigger ( $\leq 35$ KHz)

Calorimeter, Muon, Forward Detectors and Tracking triggers (XFT)

Typically about 60 L1 triggers

## L2 Trigger ( $\leq 800$ Hz)

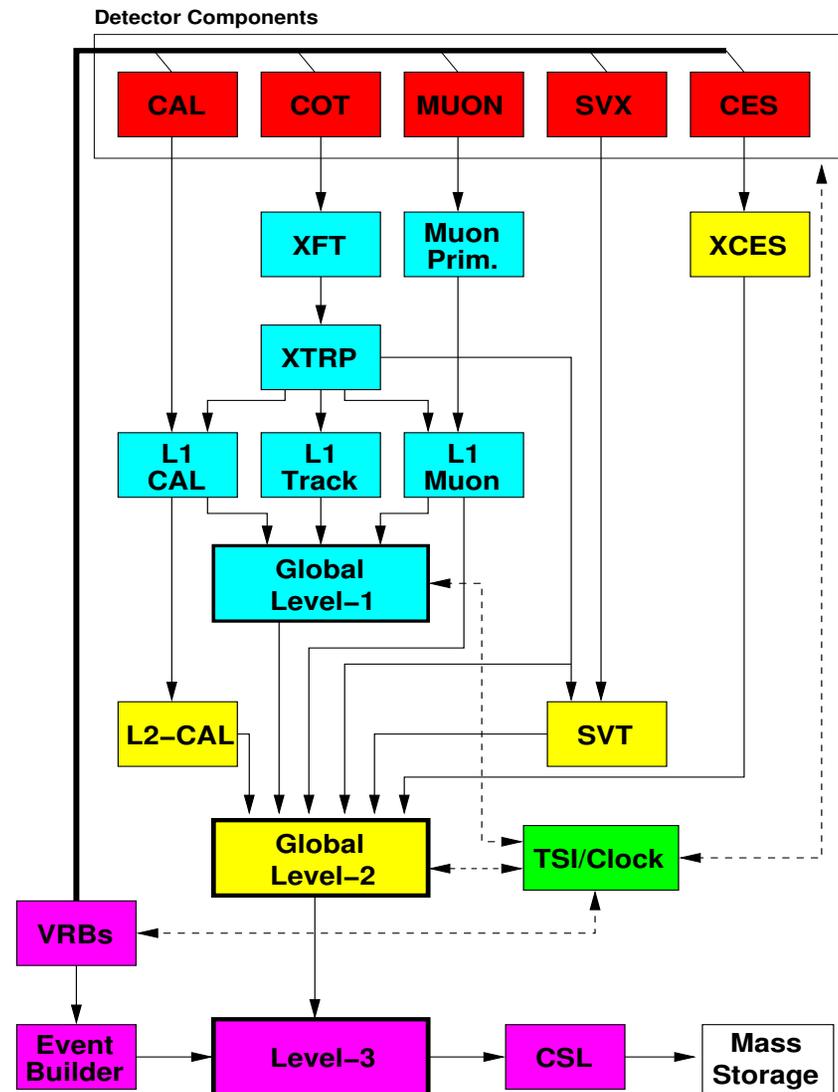
Calorimeter, *Muon* and Impact parameter triggers (SVT)

Typically about 130 L2 triggers

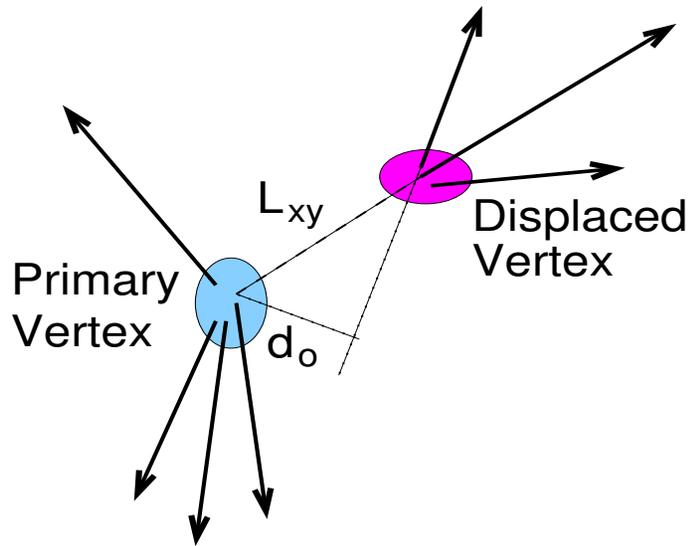
## L3 Trigger ( $\leq 100$ MB/s)

Full offline reconstruction

Typically about 200 L3 triggers



## Silicon Vertex Tracker (SVT Trigger for Run II)

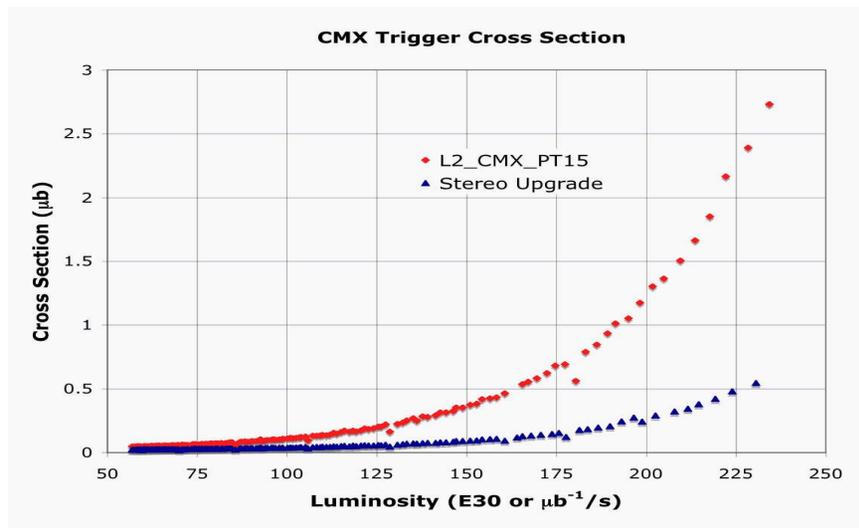


Many important physics signatures involve  $b$  quarks: *Higgs searches, top studies, constraining CKM matrix...*

$B$  particles have long lifetimes  
 $\tau(b) \sim 1.5ps$  ( $c\tau \sim 450\mu m$ )

Combine silicon hits with COT tracks; use impact parameter ( $d_o$ ) to select events with secondary vertices at the Level 2 trigger

## Trigger Upgrades for Run IIb



High  $p_T$  muons (CMX)

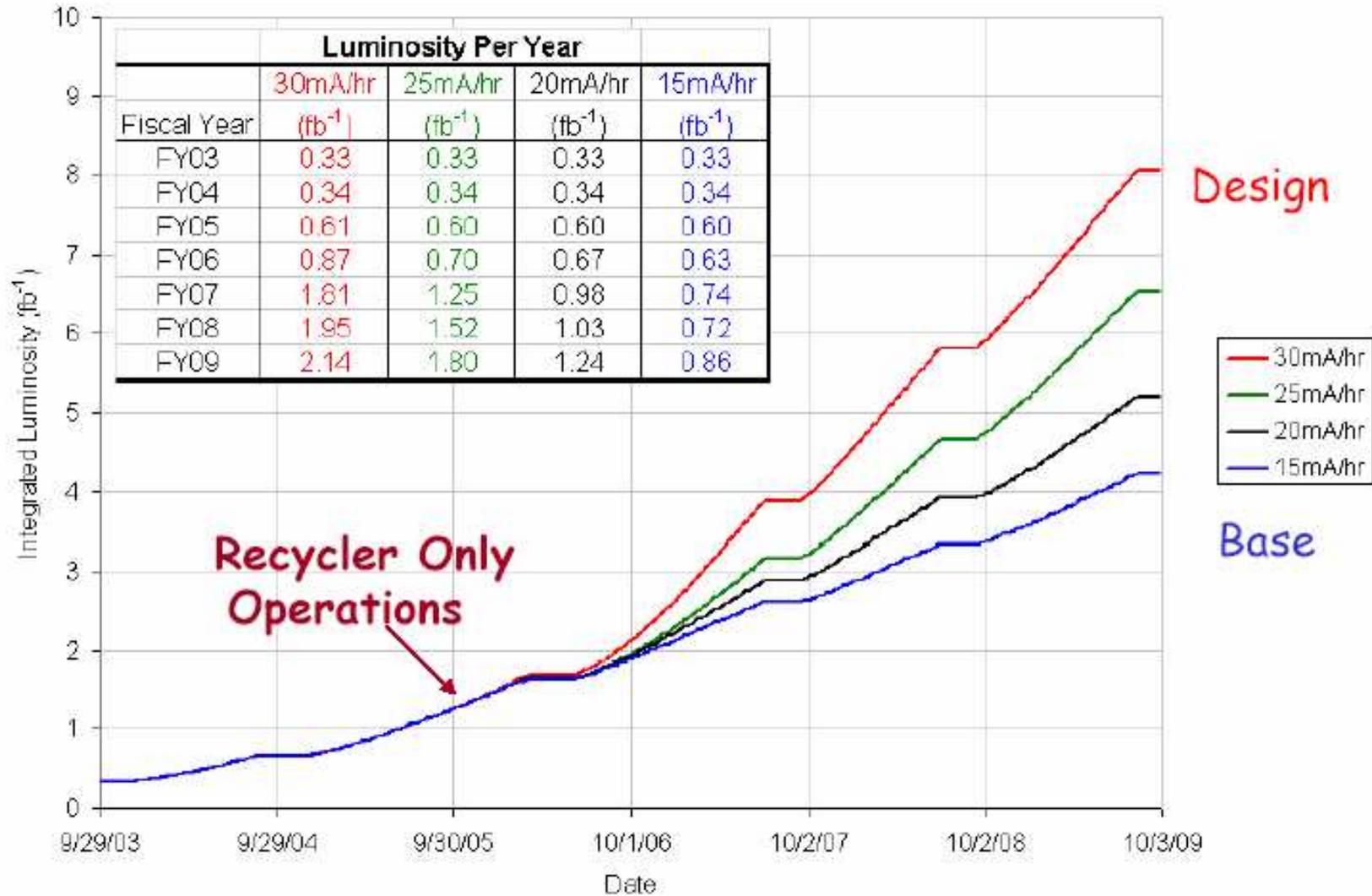
Adding COT stereo layer information to Level 1 tracks

Fake rate reduced by 4 – 5 $\times$  with only 2% loss of efficiency

→ *Additional upgrades provide improved calorimeter clustering and faster L2 decisions...*

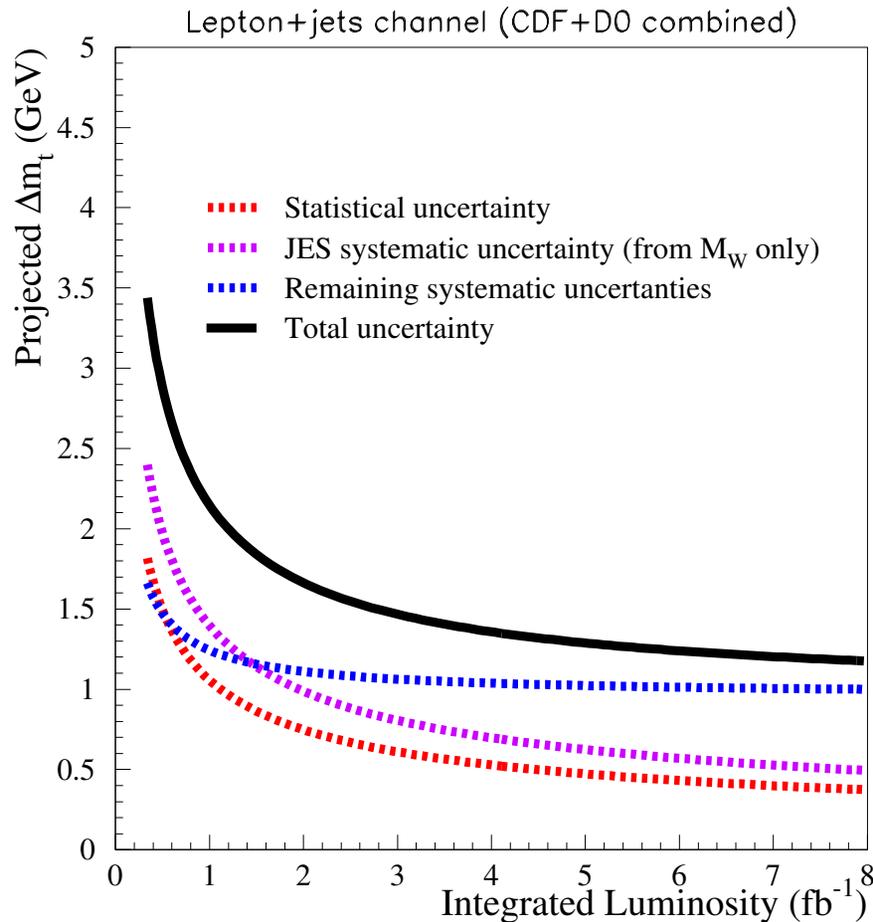
*Upgrades needed to maintain efficiency as luminosity increases*

The Tevatron has delivered  $\sim 2.7 \text{ fb}^{-1}$  of data and is projected to deliver between 4 - 8  $\text{fb}^{-1}$  by the end of 2009.



*Delivered Luminosity depends on antiproton production rate and uptime...*

# Top Mass Measurement: $\delta m_t \sim 1.5$ GeV



Similar to the uncertainty on the top mass using the basic analysis at the LHC

$$4 \text{ fb}^{-1} : \delta m_t = 1.4 \text{ GeV}$$

$$8 \text{ fb}^{-1} : \delta m_t = 1.2 \text{ GeV}$$

Projected at LHC 1.5 GeV  
(hep-ph/0412214)

Perhaps as good as 1.0 GeV  
(hep-ex/0403021)

*Expect to take several years to commission and fully understand the new LHC detectors and to process the data before precision measurements will be available...*

## Sources of systematic errors

Source	$\Delta m_t$ (GeV/c <sup>2</sup> )	
Jet Energy Scale	2.5 $\rightarrow$ 0.7	<b>Jet energy scale:</b> derived from $W \rightarrow qq'$ , detector resolution
BG shape	1.1 $\rightarrow$ 0.3	<b>Background:</b> systematic uncertainties in modeling the dominant background sources
$b$ -jet modeling	0.6	<b><math>b</math>-jet modeling:</b> variations in the semi-leptonic branching fraction, $b$ fragmentation model, differences in color flow between $b$ -jets and light quarks.
FSR	0.6	
Method	0.5 $\rightarrow$ 0.2	
ISR	0.4	<b>ISR, FSR:</b> modeling
MC statistics	0.3 $\rightarrow$ 0.1	
PDFs	0.3	<b>Method:</b> Fit method, MC statistics $b$ tagging efficiency
Generators	0.2	
$b$ -tagging	0.1	<b>Generator:</b> differences between PYTHIA or ISAJET and HERWIG when modeling the $t\bar{t}$ signal

*Adapted from Tomura, HCP2005*

*Can reduce some errors with more data*

*Reduce uncertainty by improving the modeling*

$\rightarrow$  Iterate on models and PDFs, new data has not yet been used

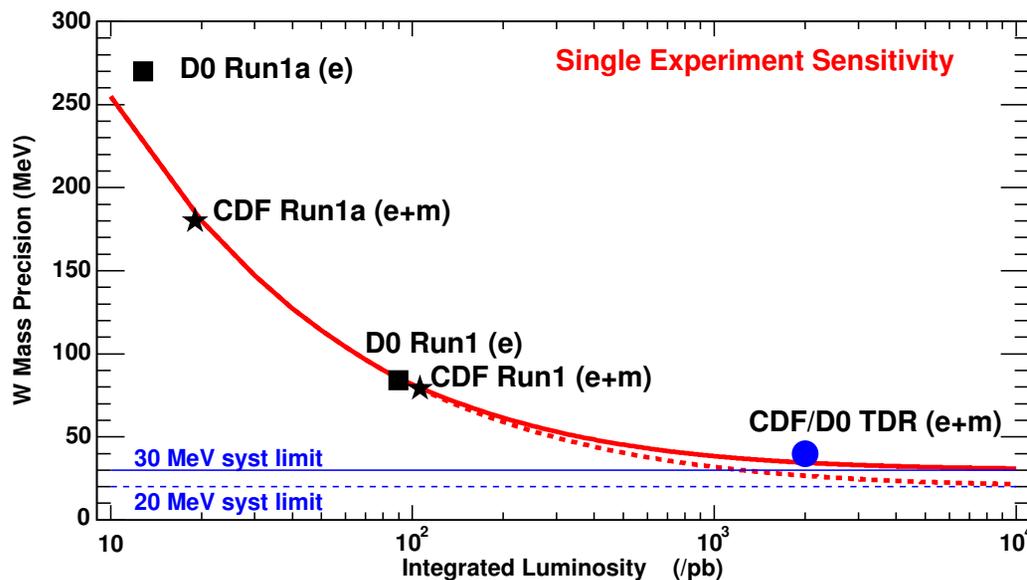
# $W$ mass measurement: $\delta m_W \sim 20 - 30$ MeV

## Uncertainties assumed to scale with luminosity

- Statistical uncertainties
- Systematic uncertainties such as: Energy and momentum scale and Hadron Recoil against  $W$

## Uncertainties assumed not to scale with luminosity

- $W$  production and decay: PDFs,  $d(\sigma_W)/d(p_T)$ , higher order QCD/QED effects (Assumed to be between 20 - 30 MeV)



LHC expectations are:

$$\delta m_W \sim 10 - 20 \text{ MeV}$$

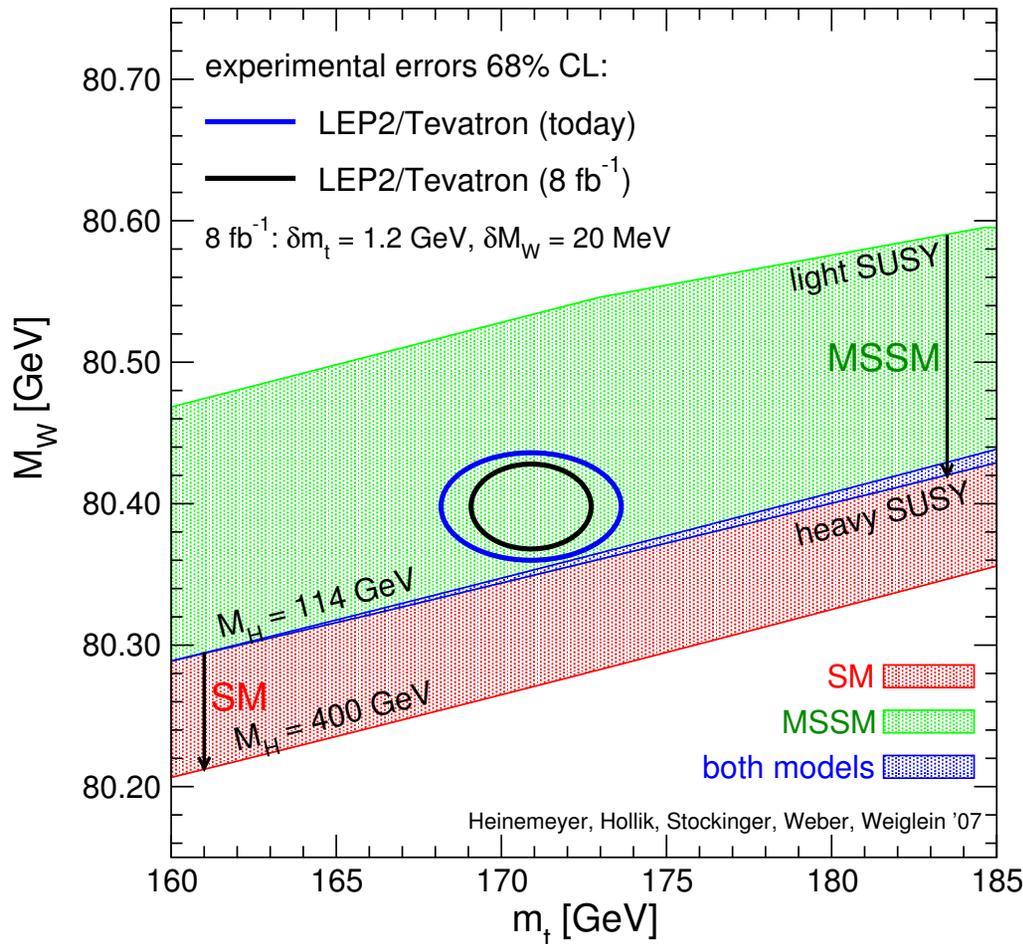
Requires:

→ *low luminosity running*

→ *good understanding of the detector*

# The $M_W - M_{\text{Top}} - M_{\text{Higgs}}$ Relationship

A key test of the Standard Model is a consistency between the  $W$ , Top and Higgs mass.



$$M_W = 80.398 \pm 0.025 \text{ GeV}$$

$$M_{\text{top}} = 170.9 \pm 1.8 \text{ GeV}$$

Direct searches at LEP:

$$M_{\text{Higgs}} > 114 \text{ GeV} \quad 95\% \text{ CL}$$

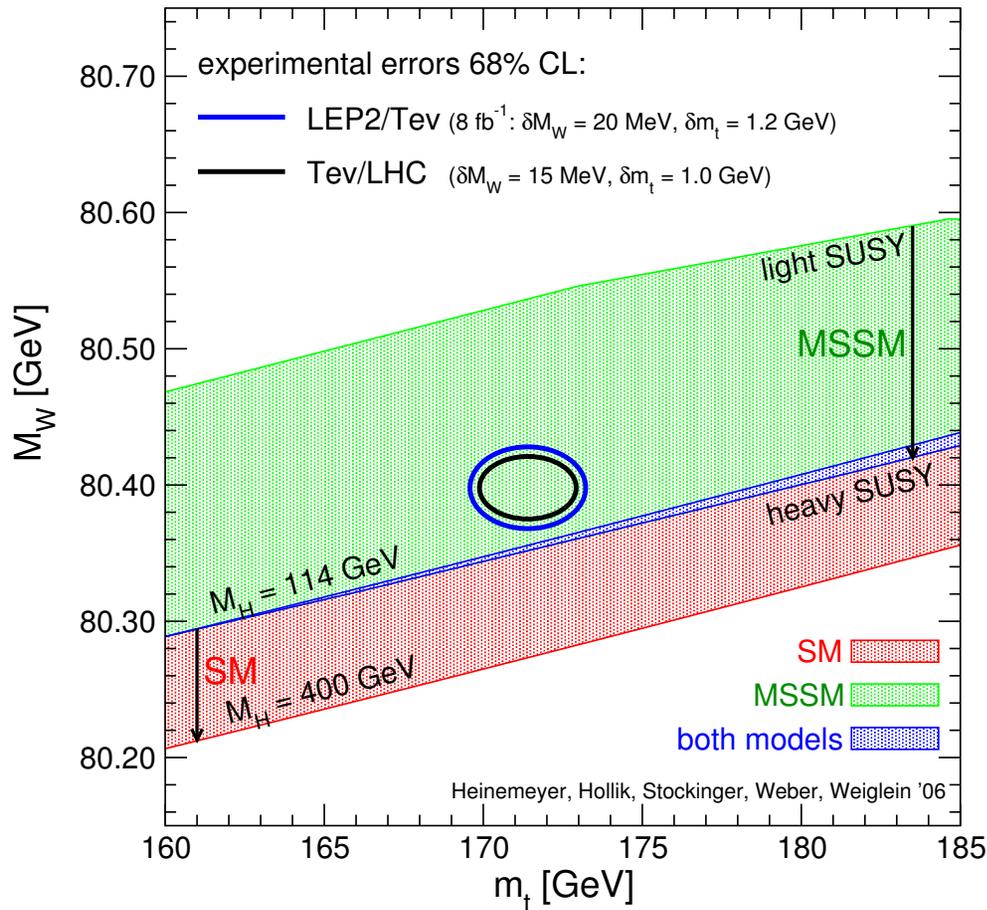
Indirect measurements favor a low mass Higgs

$$M_{\text{Higgs}} = 76^{+33}_{-24} \text{ GeV}$$

$$M_{\text{Higgs}} < 144 \text{ GeV} \quad 95\% \text{ CL}$$

*68% CL ellipse now outside the SM Higgs region...*

# Comparison of the projected precision for the W and Top mass for the Tevatron and LHC

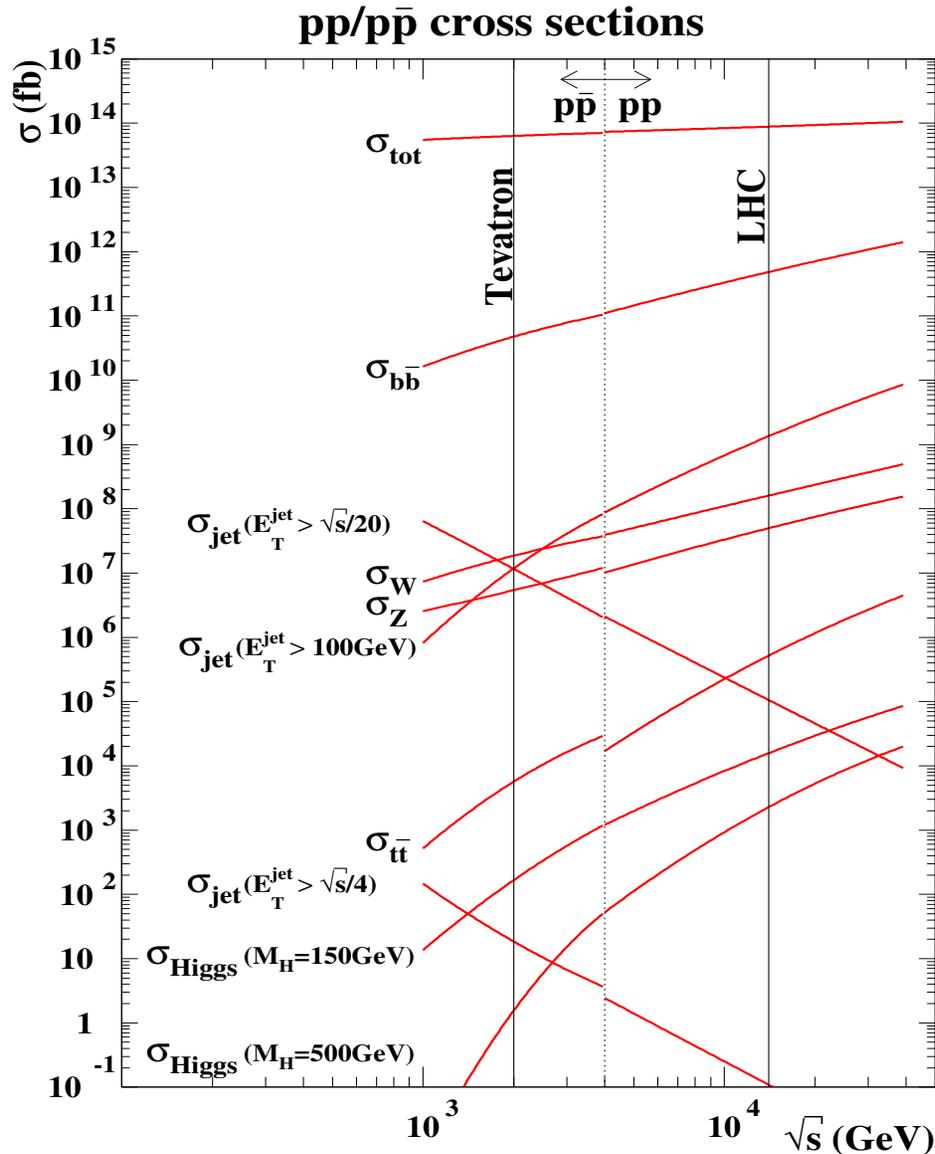


With  $8 \text{ fb}^{-1}$  of data, the Tevatron can provide a competitive measurement of both the top and  $W$  mass to what is expected from the LHC.

*Future experiments such as ILC/GigaZ needed for more dramatic improvements*

*S. Heinemeyer, W. Hollik, D. Stockinger,  
A.M. Weber, G. Weiglein '06*

# Understanding the Backgrounds



New physics has small cross sections and is swamped by standard physics background

Standard physics processes have relatively large uncertainties

→ *Need to have an accurate prediction for backgrounds in order to claim a discovery*

# Understanding the Underlying Event

The underlying event (UE) is an unavoidable background to many measurements at the Tevatron and the LHC.

*There is also interesting QCD physics in the UE which contains particles originating from initial and final state radiation, beam-beam remnants, and multiple parton interactions.*

Don't think we have a satisfactory description of the UE in MC

→ *PYTHIA has only a few parameters available to tune UE*

→ *PYTHIA 6.3 provides additional handles*

→ *No handles in HERWIG*

→ *Add JIMMY to HERWIG*

*Can we find “universal tunes”... HERA → Tevatron → LHC*

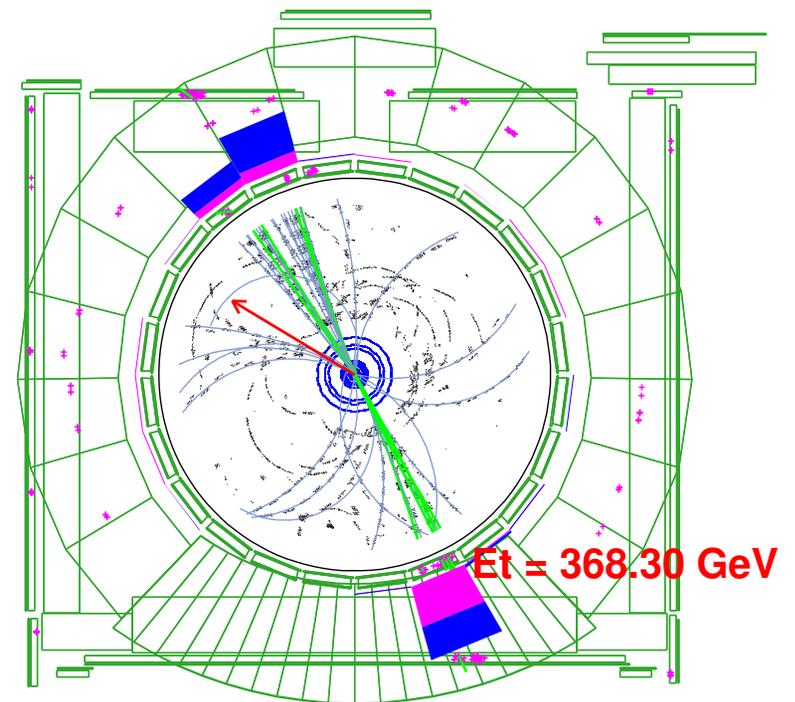
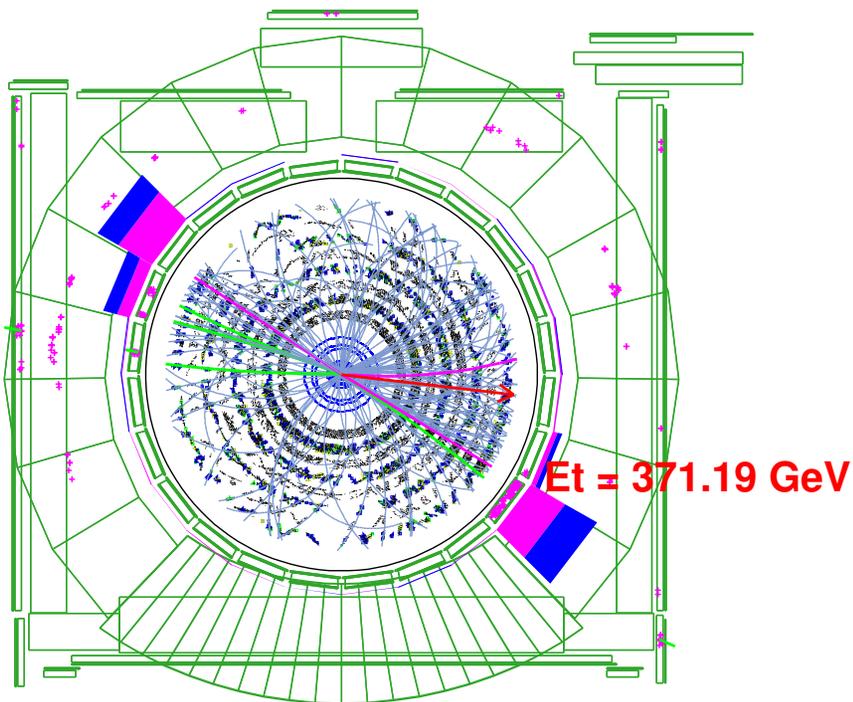
Do have the possibility to help tune the models...

→ *Measure the cross-section for multiple-parton collisions and establish precisely how much it contributes to the UE in various processes.*

→ *Multiplicity distributions in  $W$ ,  $Z$ , Drell Yan,  $WW$ ,  $ZZ$ , and  $WZ$*

→ Study the UE in color singlet production (Z-boson and Drell Yan processes). Compare to the UE in high  $p_T$  jet production.

→ Determine rate of vector boson fusion (VBF) and study rapidity gaps.



Understanding of the UE will be among the first things needed at the LHC. *Also probably one of the first things studied...*

# Parton Density Function Uncertainties

Errors on PDFs can influence measurements at several stages

$$\sigma_{\text{meas}} = \frac{\epsilon}{\mathcal{L}}(N_{\text{obs}} - N_{\text{bkg}})$$

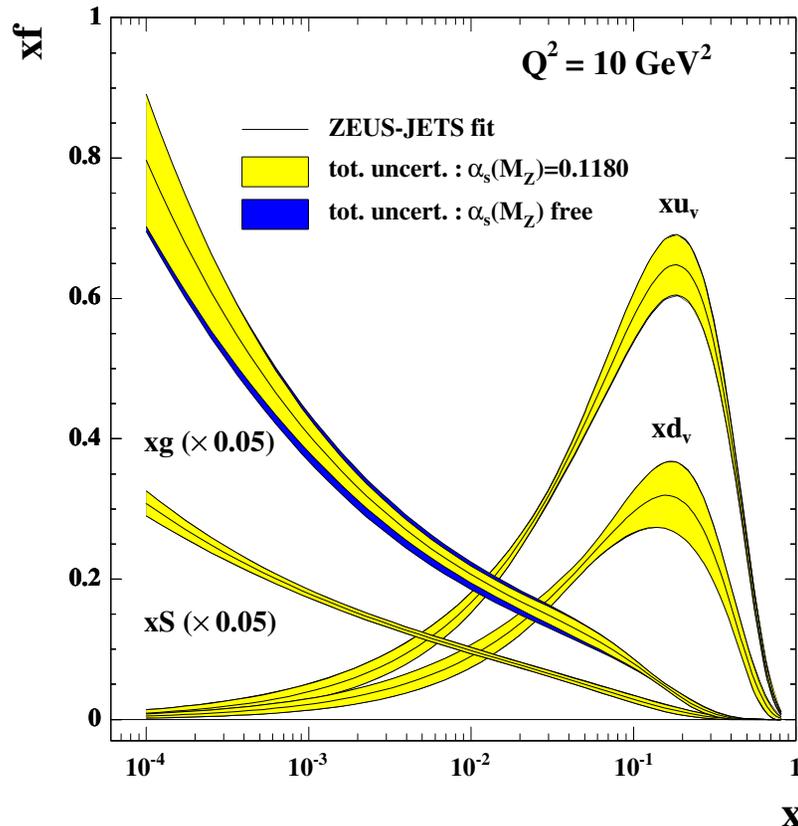
*Calculation of acceptance ( $\epsilon$ ), luminosity ( $\mathcal{L}$ ), event selection ( $N_{\text{obs}}$ ), background estimate ( $N_{\text{bkg}}$ )*

$$\sigma_{\text{theory}} = \text{PDF}(x_1, x_2, Q^2) \otimes \sigma_{\text{hard}}$$

*Theory calculation includes:*

- Experimental errors when fitting measured data
- Theoretical errors resulting from input parameters (flavor threshold,  $\alpha_s$ ...) uncertainties on the theoretical modeling (scale errors, nonperturbative effects, PDF parameterization...)

# Parton Density Functions



Particle structure is parameterized by PDFs → gives the probability of probing a parton of a given type

PDFs (up, down gluon, sea) are parameterized as a function of the kinematic variables  $(x, Q^2)$

$x$  : momentum fraction carried by the struck parton

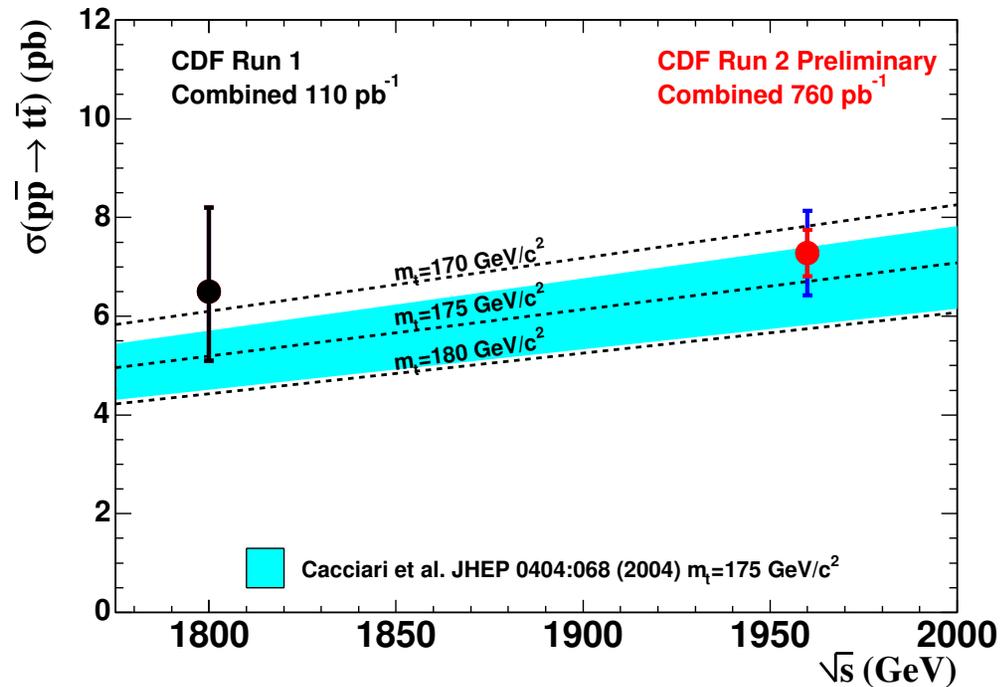
$Q^2$  : the square of the momentum transferred

The Standard Model (QCD, electroweak...) describes how the partons interact with each other.

→ Cross sections (predictions) can then be calculated once you know the probability of probing particular partons

# Top Cross Section

Inclusion of full PDF systematics leads to a more realistic estimate of the top cross section uncertainty



For  $m_t = 175$  GeV

$$\sigma = 6.70 \pm 0.45 \text{ pb} \quad (CTEQ6M)$$

$$\sigma = 6.76 \pm 0.21 \text{ pb} \quad (MRST2001)$$

→ Dominated by PDF and  $\alpha_s$  uncertainties

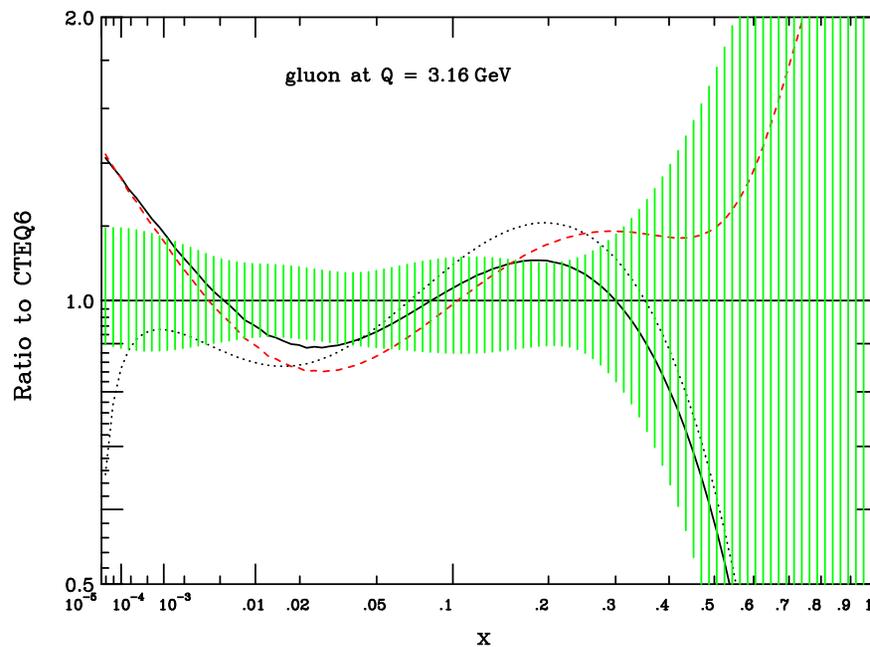
*Cacciari et al (hep-ph/0303085)*

$\pm 3 - 6\%$  error mainly arising from uncertainty of large- $x$  gluons

→ *Measurement error approaching the size of the error on the calculation...*

→ *New inclusive jet data has not yet been used to produce newer PDF sets...*

# Input to PDFs - What is Unknown



## Gluon distribution

→ *Inclusive jet, forward jets*

Shaded band shows the CTEQ6 gluon uncertainty at  $Q^2 = 10 \text{ GeV}^2$

Ratio of CTEQ5M (solid), CTEQ5HJ (dashed) and MRST2001 (dotted) to CTEQ6

hep-ph/0201195

## Strange and anti-strange quarks, strange asymmetry

→ *Tagged final states  $W/Z/\gamma + c/b$*

## Details in the $u, d$ quark sector, $u/d$ ratio

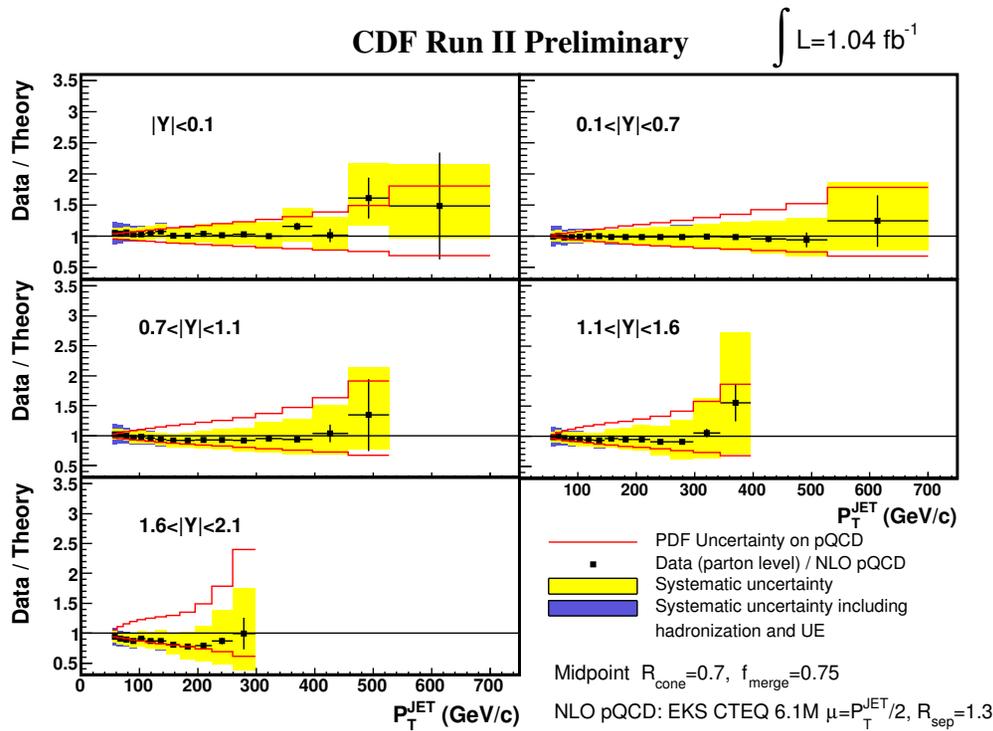
→  *$W$  charge asymmetry*

→  *$W$  rapidity distribution*

## Heavy quark distribution

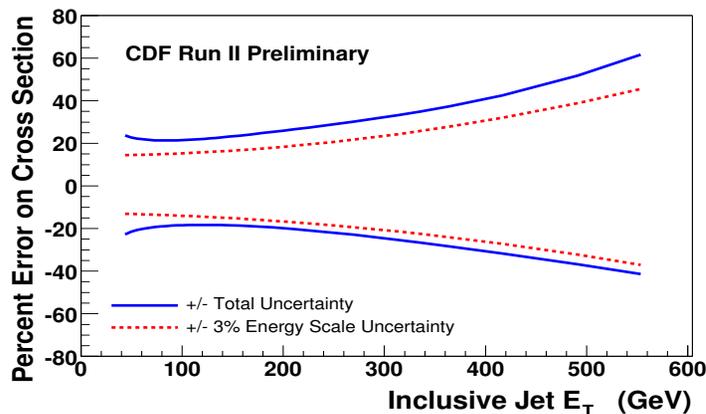
→ *Tagged final states  $W/Z/\gamma + c/b$*

Inclusive jet cross section  $\rightarrow$  *probes the high  $x$  gluon distribution*



PDF parameterization could accommodate deviations at high  $p_T$

*Need to measure jets in the forward region to separate “old physics from new”*

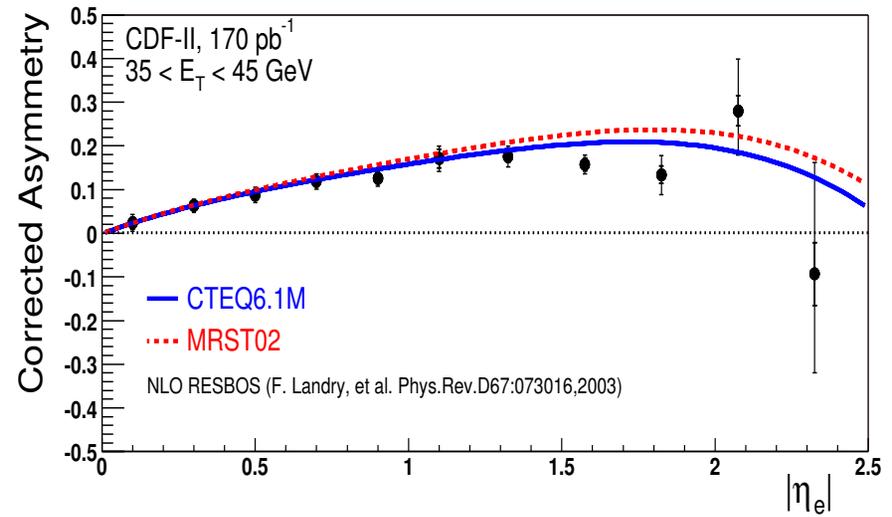
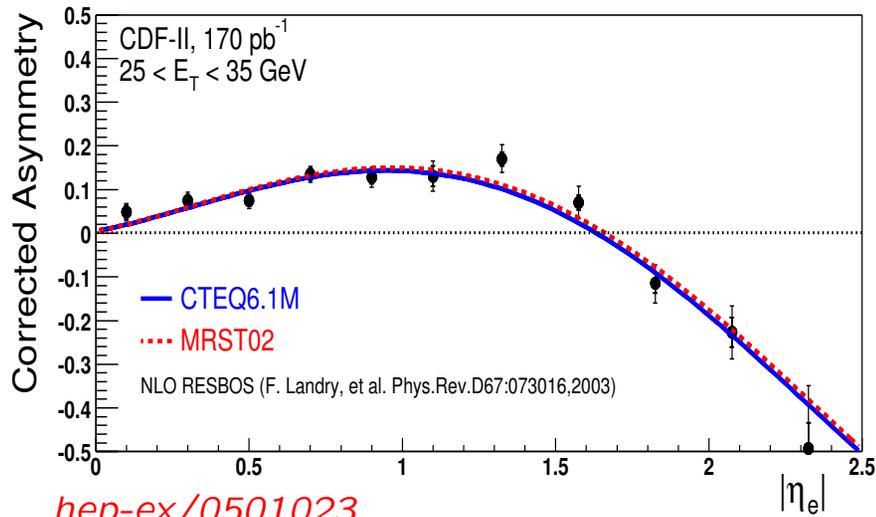


Measurement is systematics limited

$\rightarrow$  *Energy scale is the dominant source of systematic error*

## W Charge Asymmetry

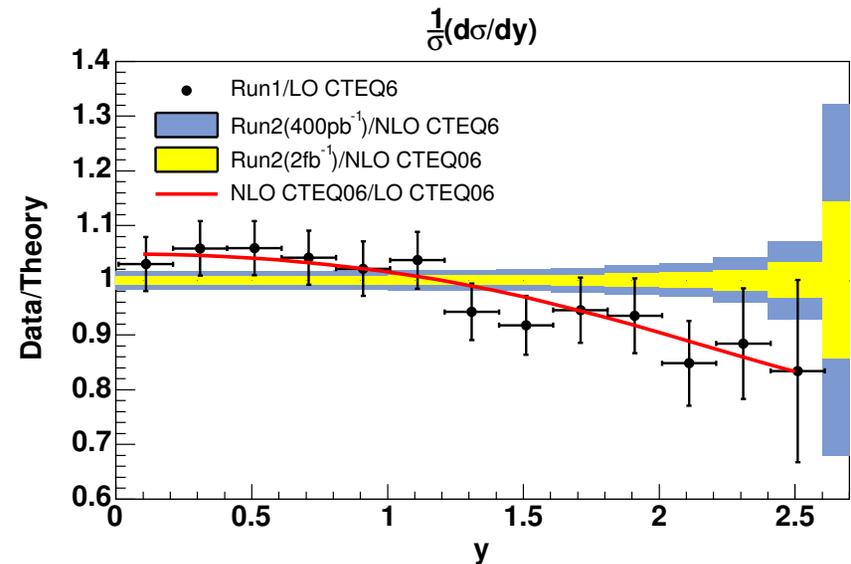
$$A_{ch}(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \sim \frac{d(x, M_W)}{u(x, M_W)}$$



## Z Rapidity Distributions

Bands show expected reduction in the statistical error for 400pb<sup>-1</sup> and 2fb<sup>-1</sup>

*Currently not being used in fits... but may be promising*



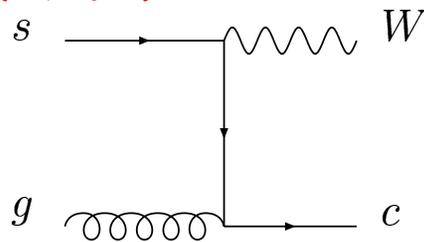
# Intrinsic Heavy Quark

Very little direct experimental input

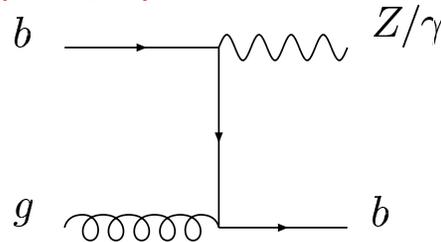
→ All  $c$  and  $b$  distributions in existing PDF sets are generated by gluon splitting (radiatively generated)

→ No degrees of freedom are associated with the heavy flavor in the global QCD fits

$s(x, Q^2)$

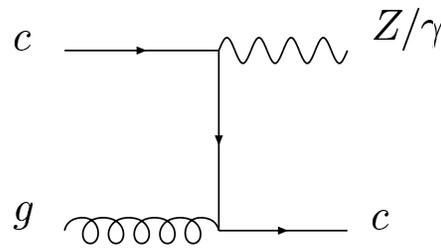
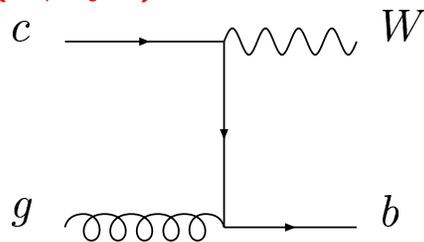


$b(x, Q^2)$



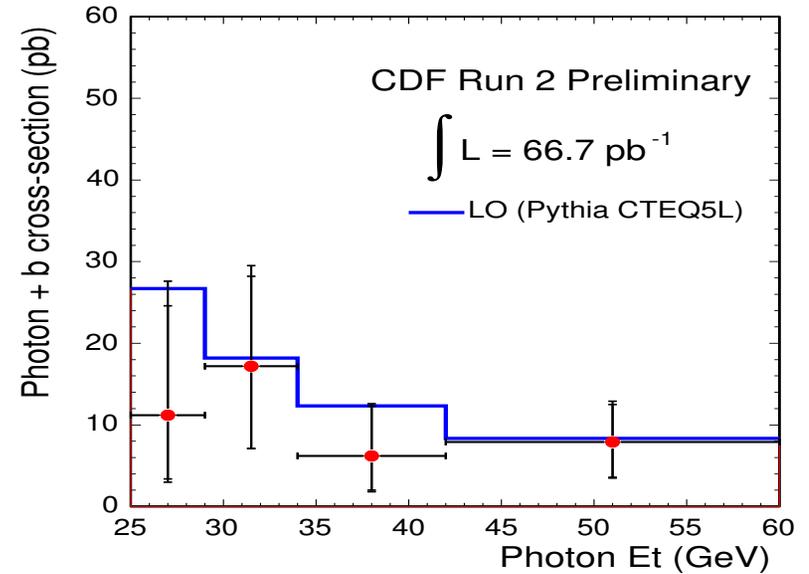
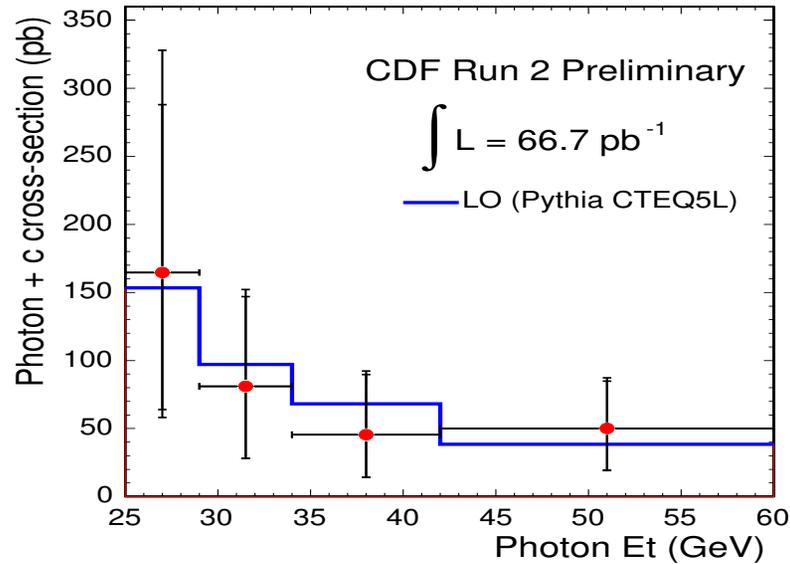
Probe sea quark distributions with tagged final states  $W/Z/\gamma + c/b$

$c(x, Q^2)$



→ Influence on physics analysis of the next generation of experiments is expected to be increasingly important

# $\gamma$ plus Tagged Heavy Flavor



Dominated by statistical errors

Largest systematic errors

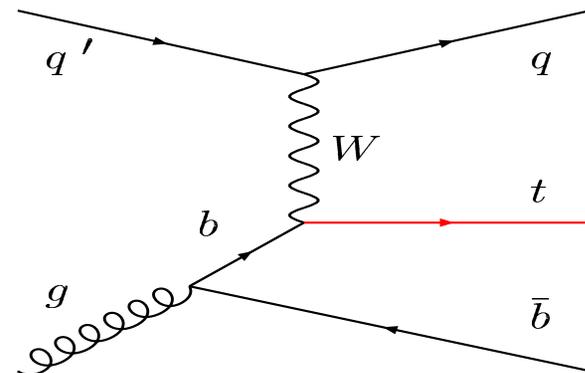
→ *Energy scale*

→ *Tagging Efficiency*

→ *Trigger*

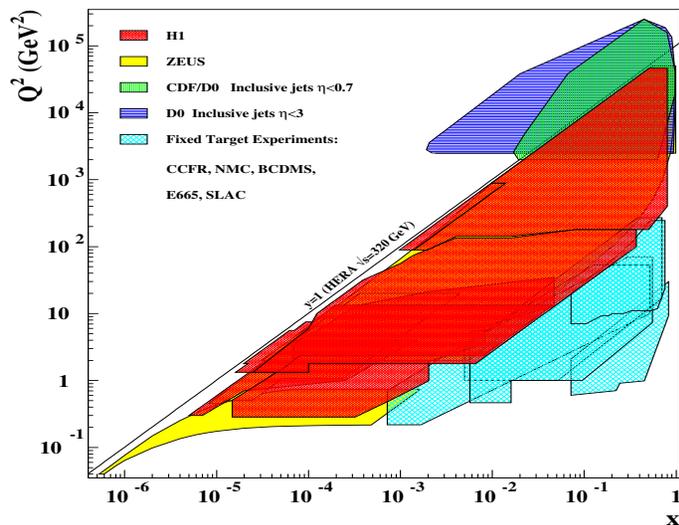
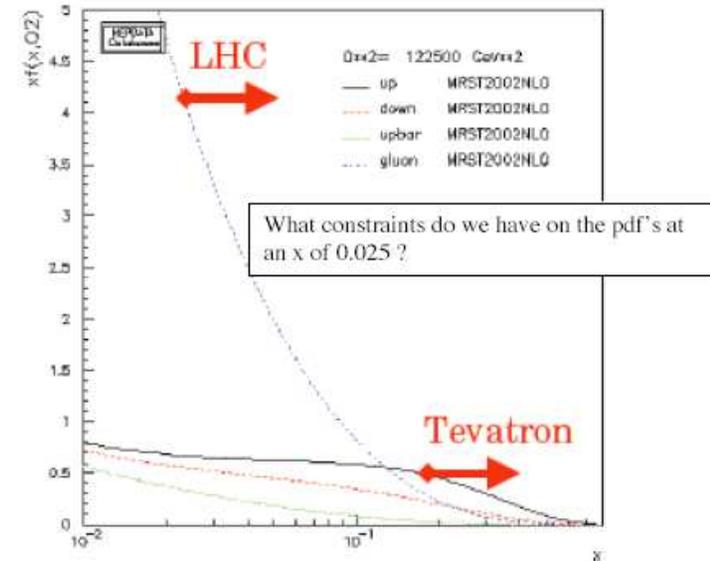
Can we constrain intrinsic heavy flavor at the Tevatron?

Single top production also probes  $b$  quarks at high  $x$



# Tevatron and LHC access different kinematic regions

The ability to distinguish new physics from Standard Model predictions depends on how well we can extrapolate predictions to the new kinematic region



## PDFs are “Universal”

PDFs can lead to different predictions depending on parameterizations and on datasets used in the fits

→ *Should include as much data in the global fit as possible*

*Demonstrate consistency between measurements in different regions of phase space as well as between different processes*

# Di-Boson Production

Di-Boson cross section measurements provides tests of the SM and probes boson self couplings.

$ZZ/ZW$  production probes the triple gauge boson couplings.

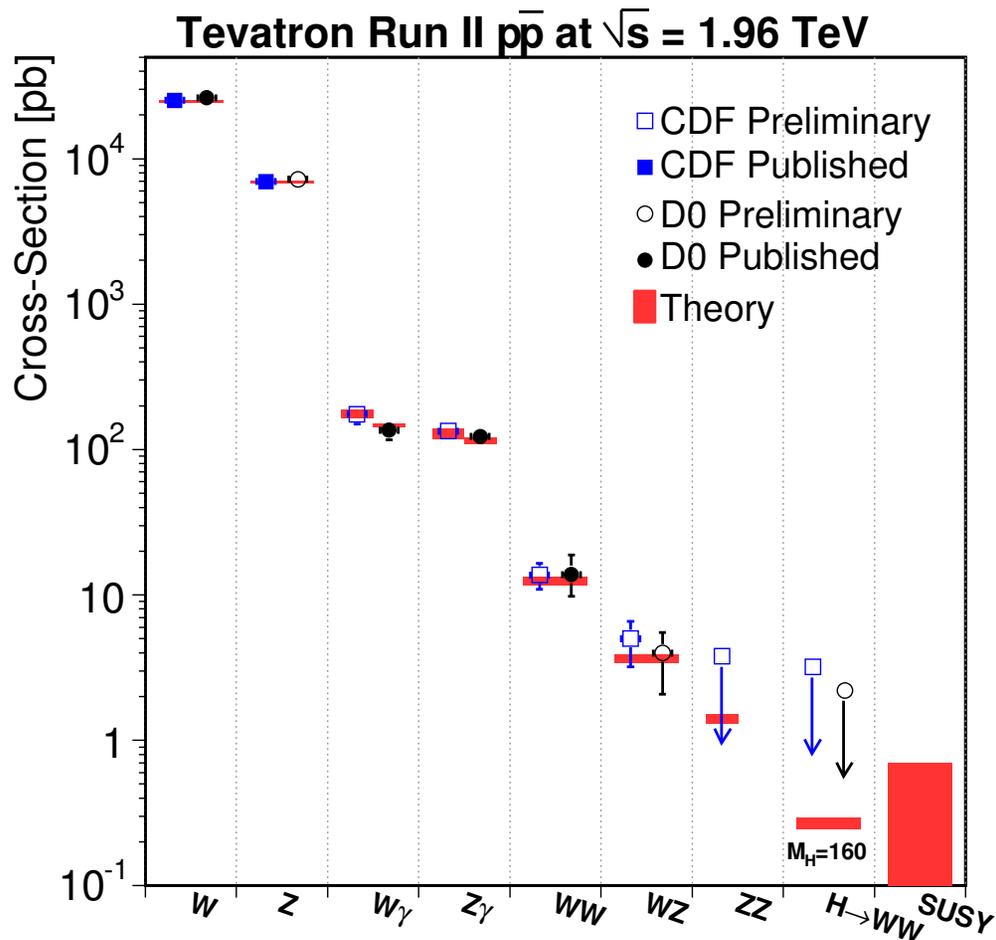
→ *The presence of unexpected neutral triple-gauge-boson couplings ( $ZZZ$  and  $ZZ\gamma$ ) can lead to enhanced  $ZZ$  production.*

→ *Anomalous  $WWZ$  coupling can increase the  $ZW$  production rate above the SM predictions.*

A good understanding of Di-Boson production is needed to estimate the background for other important physics.

→ *In  $t\bar{t}$  events when the  $W$ s decay leptonically signature is similar to  $WW$  production.*

→ *The production of  $WZ$  and  $ZZ$  boson pairs is a significant background in searches for the SM Higgs.*



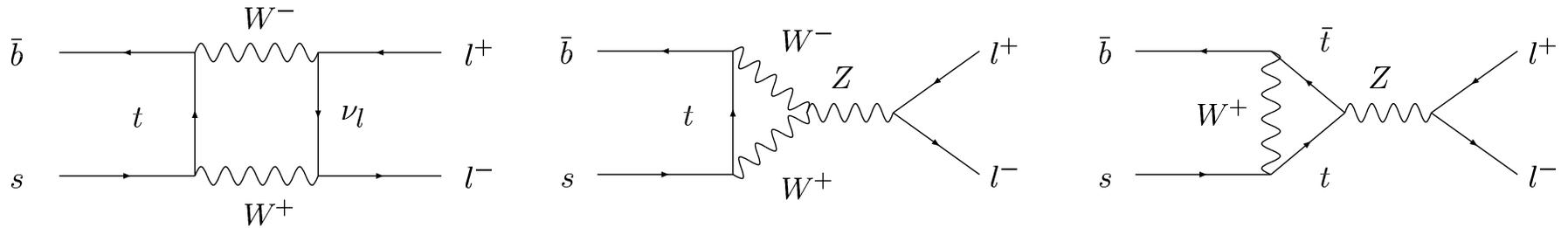
Uncertainty on the cross section for the  $WW$  process is  $6 - 7 \times$  the theoretical uncertainty.

Now with  $\sim 1.5$  fb of data CDF has a  $3\sigma$  significant evidence of a signal for  $ZZ$  production

*Similar footing as single top production, and needs comparable statistics for a good description.*

Di-Boson production is an important background for Higg's searches  
 $gg \rightarrow H \rightarrow WW$

# Search for FCNC



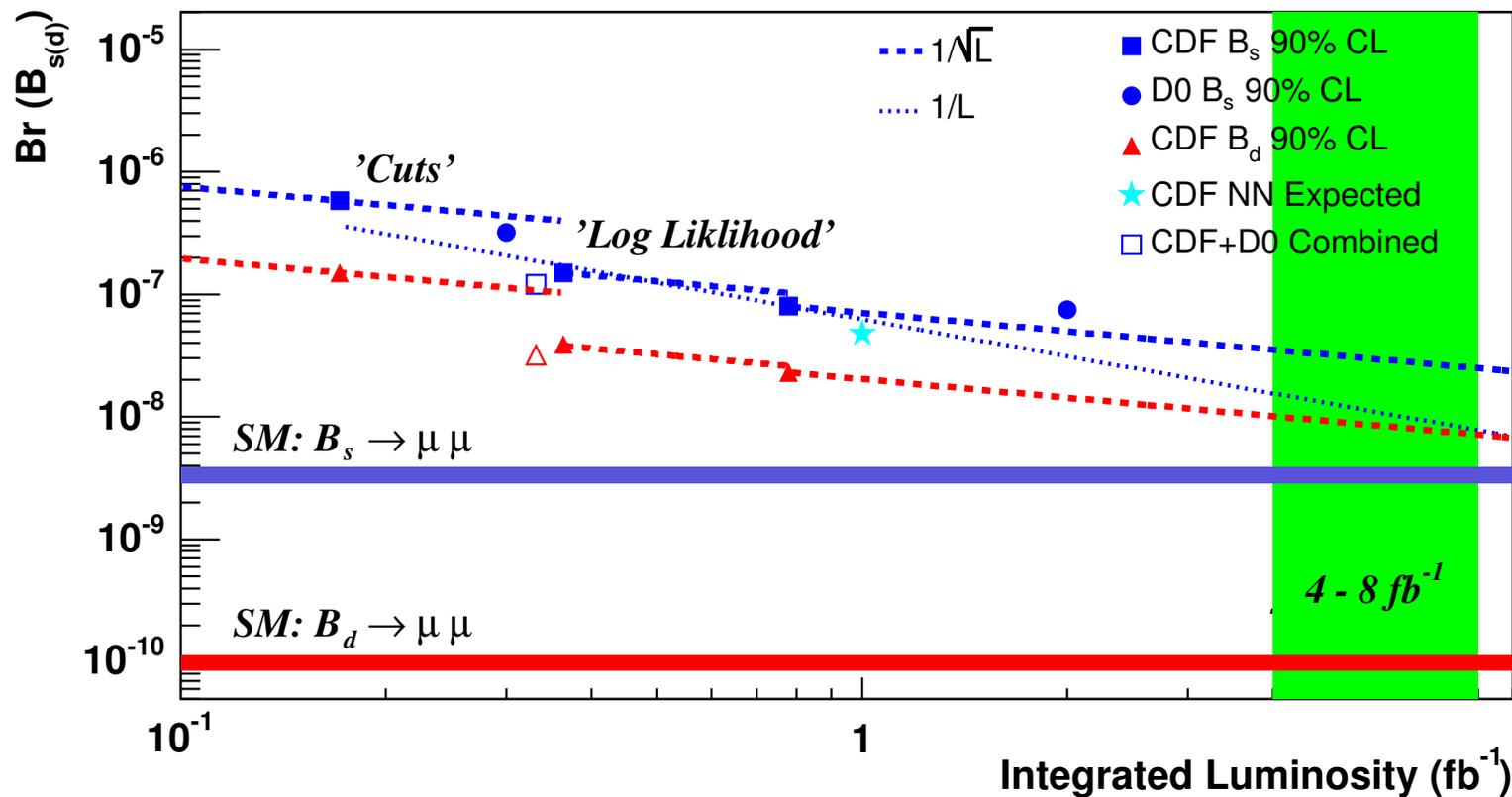
Flavor Changing Neutral Current decays are highly suppressed in the SM

$$Br(B_s^0 \rightarrow \mu^+ \mu^-) \sim 10^{-9} \quad \propto \text{the CKM matrix element } |V_{ts}|^2$$

$$Br(B_d^0 \rightarrow \mu^+ \mu^-) \sim 10^{-10} \quad \text{further suppressed by } |V_{td}/V_{ts}|^2$$

*New Physics contributions can significantly enhance the branching fractions and observation at the Tevatron would be a signature of new physics*

# Summary of limits on $B_{s(d)} \rightarrow \mu^+ \mu^-$



*Improvement over first measurement results from a better separation of signal from background ("cuts" → "log likelihood")*

*→ Neural Net method is expected to have greater sensitivity*

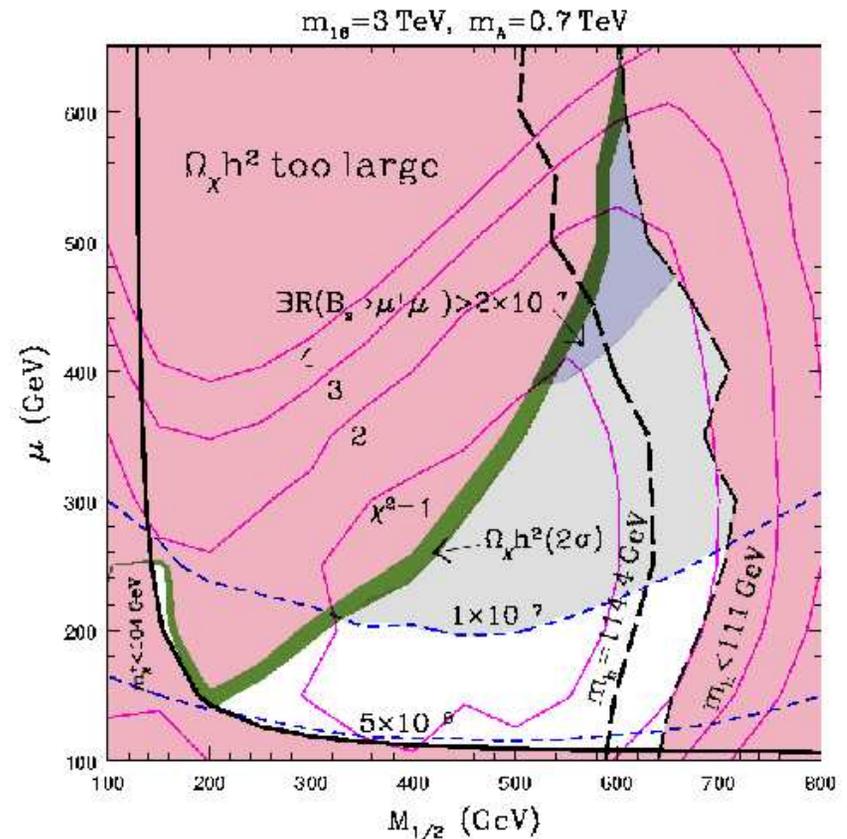
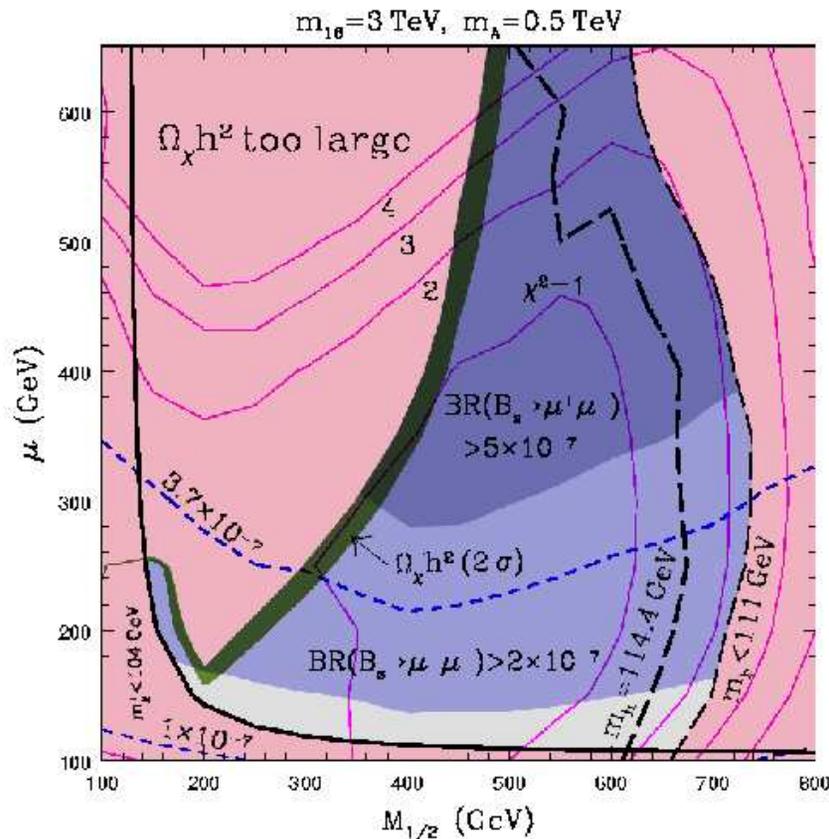
*→ Combine CDF + DØ results for greater reach...*

*Improvements scaling faster than  $1/\sqrt{\mathcal{L}}$ , more like  $1/\mathcal{L}$*

Best limit from  $D\emptyset$  based on  $\sim 2 \text{ fb}^{-1}$

$$Br(B_s^0 \rightarrow \mu^+ \mu^-) < 7.5 \text{ (9.3)} \times 10^{-8} \quad 90\% \text{ (95\%)} \text{ CL}$$

*More phase space excluded in SUSY SO(10)*

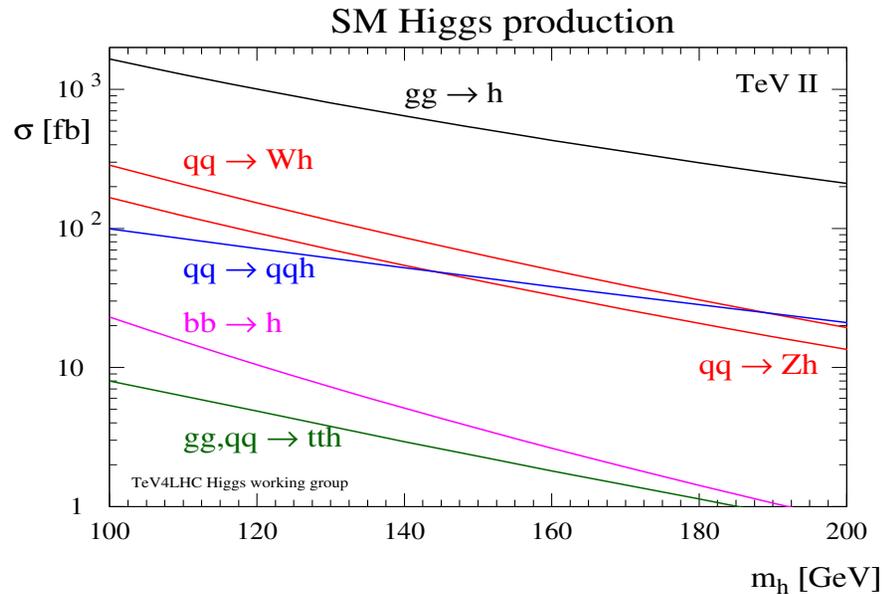


*R.Dermisek et al., IHEP 0304 (2003) 037*

*R.Dermisek et al., hep-ph/0507233 (2005)*

→ *Better limits expected once we have the full data set analyzed*

# Searching for the Higgs



Direct searches at LEP:

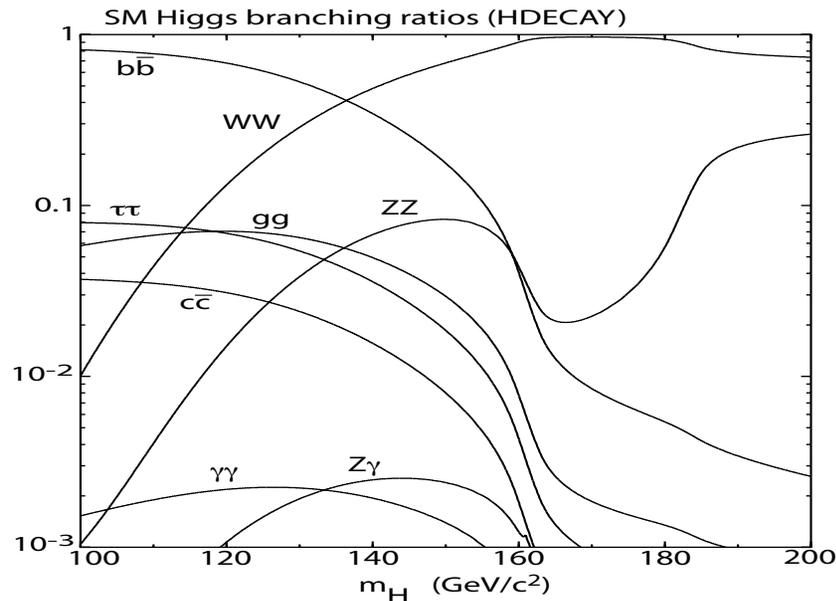
$$M_{\text{Higgs}} > 114 \text{ GeV } 95\% \text{ CL}$$

Indirect measurements suggest:

$$M_{\text{Higgs}} = 76^{+33}_{-24} \text{ GeV}$$

$$M_{\text{Higgs}} < 144 \text{ GeV } 95\% \text{ CL}$$

*Tevatron Reach < 180 GeV*



Dominant mode

$$gg \rightarrow H \rightarrow b\bar{b}$$

$\sigma_{b\bar{b}}$  is huge!

*Look for channels that are easier to separate from background*

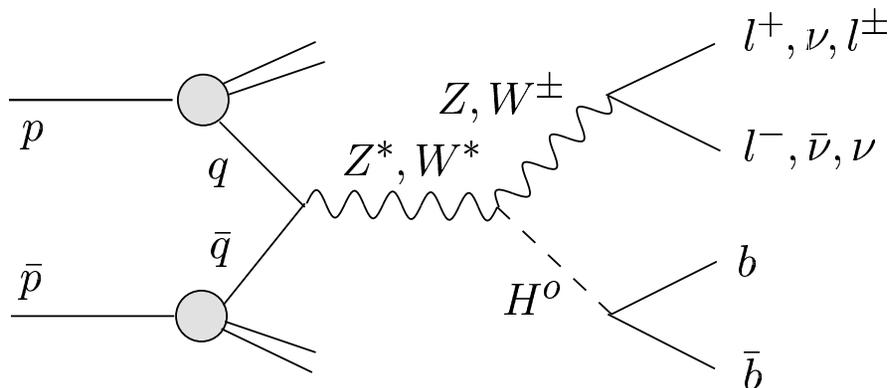
## Expected event yields for SM Higgs production

Production	Decay	Rel. BR	Evts, $2fb^{-1}(M_H)$
$qq \rightarrow VH$	$H \rightarrow b\bar{b}$	$W \rightarrow qq$	(120 GeV) 145
		$Z \rightarrow qq$	92
		$W \rightarrow (e/\mu)\nu$	50
		$Z \rightarrow \nu\nu$	28
		$W \rightarrow \tau\nu$	25
		$Z \rightarrow ee/\mu\mu$	10
		$Z \rightarrow \tau\tau$	5
$qq \rightarrow VH$	$H \rightarrow WW \rightarrow l\nu l\nu$	$W \rightarrow qq$	(160 GeV) 7
		$Z \rightarrow qq$	5
		$W \rightarrow l\nu$	4
		$Z \rightarrow ll$	0.7
		$Z \rightarrow \nu\nu$	1.5
$gg \rightarrow H$	$H \rightarrow WW$	$WW \rightarrow (e/\mu)\nu qq$	(160 GeV) 160
		$WW \rightarrow e\tau/\mu\tau/\tau\tau\nu\nu$	33
		$WW \rightarrow ee/\mu\mu/e\mu\nu\nu$	27
$gg \rightarrow H$	$H \rightarrow b\bar{b}$		(120 GeV) 950
$gg \rightarrow H$	$H \rightarrow \tau\tau$	with one $\tau \rightarrow l\nu$	(120 GeV) 56

Need to fold in trigger efficiency, detector acceptance, reconstruction efficiency, background estimate...

# Higg's Search Channels - Low Mass

Main search channels from associative production



For  $m_H < 135$  GeV,  
 $b\bar{b}$  decays dominate

$$ZH \rightarrow l^+ l^- b\bar{b}$$

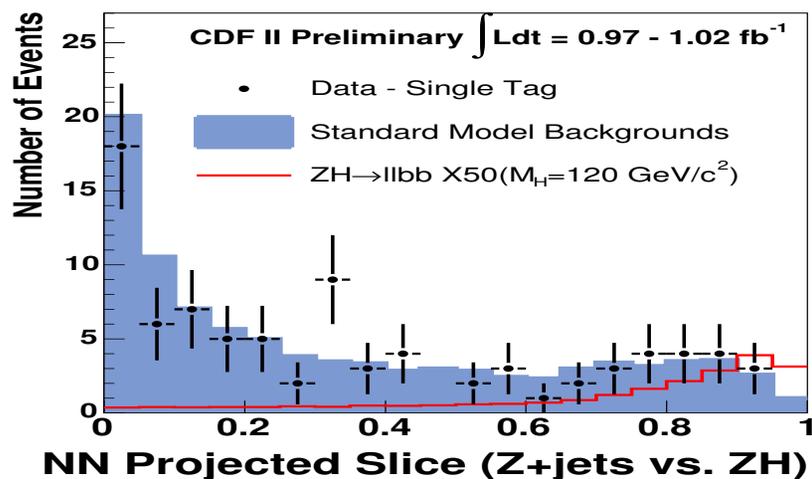
$$ZH \rightarrow \nu\bar{\nu} b\bar{b}$$

$$W^\pm H \rightarrow l^\pm \nu b\bar{b}$$

## Requires:

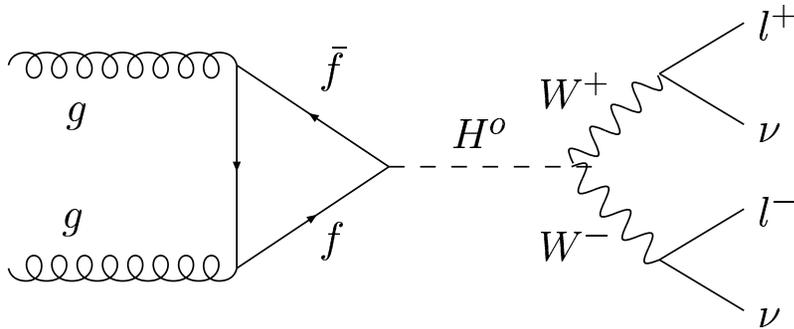
- Excellent  $b$  tagging
- Optimal  $b\bar{b}$  mass resolution
- Missing  $E_T$
- Lepton tagging
- Understanding of background
- Separation of signal from background

Search for SM Higgs in  $ZH \rightarrow l^+ l^- b\bar{b}$



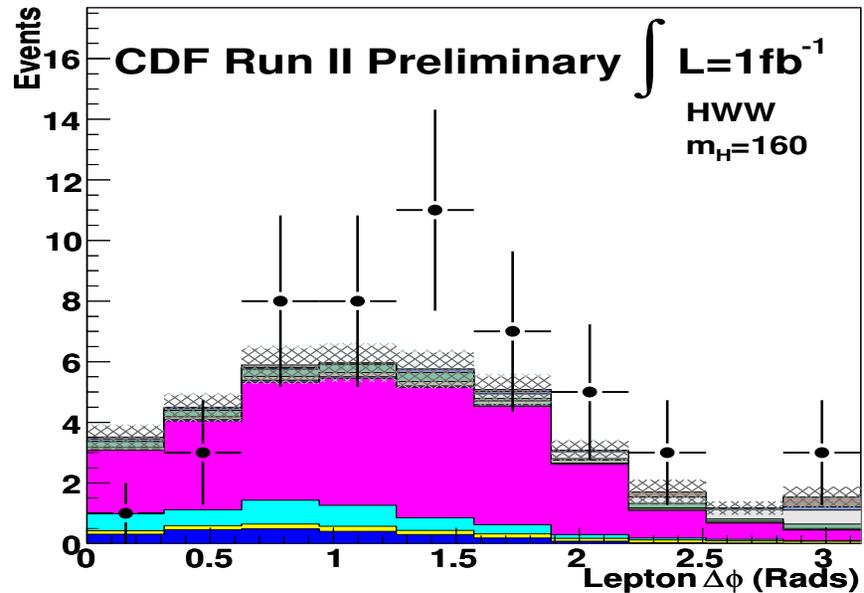
Signal  $\times 50$

# Higg's Search Channels - High Mass



$$gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$$

Select events with two high  $p_T$  leptons ( $ee, e\mu, \mu\mu$ )

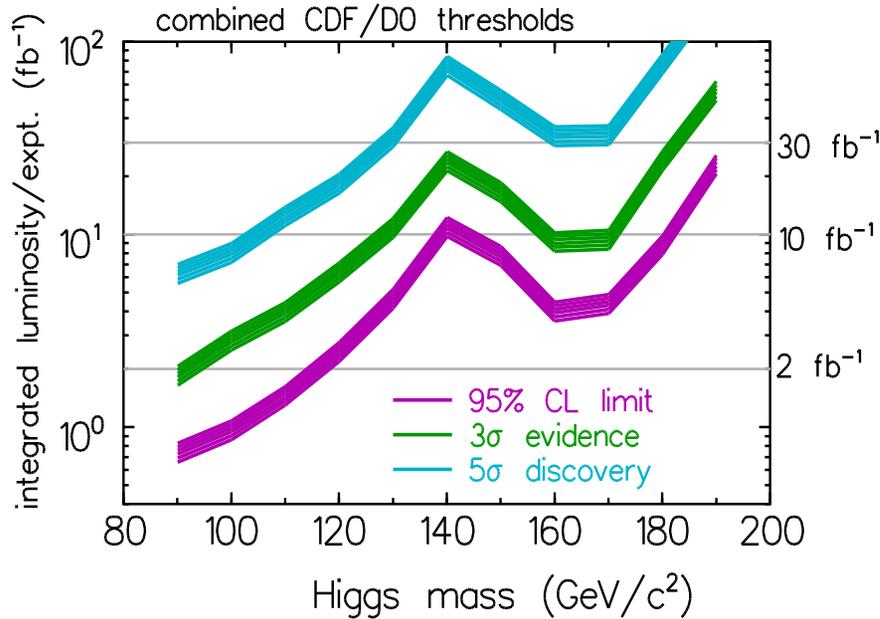


Understand backgrounds  
 $WW, W\gamma$

Initial analysis used "cuts" to separate signal from background

*New analyses are using more sophisticated techniques used to better separate signal from background*

*SUSY Higgs Working Group (1998-99)*



CDF and DØ combined sensitivity for all channels

- *Upgraded Silicon*
- *10% mass resolution (crutial)*
- *Advanced techniques (Neural Net event selection)*

*Where we are*

Higgs Mass	CDF Current Limit/SM	Expected	Combined CDF + DØ
115 GeV	11.3	8.0	~ 5
160 GeV	3.1	4.9	~ 3

25× more data at low mass  
10× more data at high mass

Some analysis improvements outperform assumptions in the 1998-99 study → 2D NN rejects  $t\bar{t}$  better, mass resolution improvement tools specific to  $llbb$

*Both the NN and matrix element techniques are vast improvements on the old cut-based analyses*

## Areas to work on:

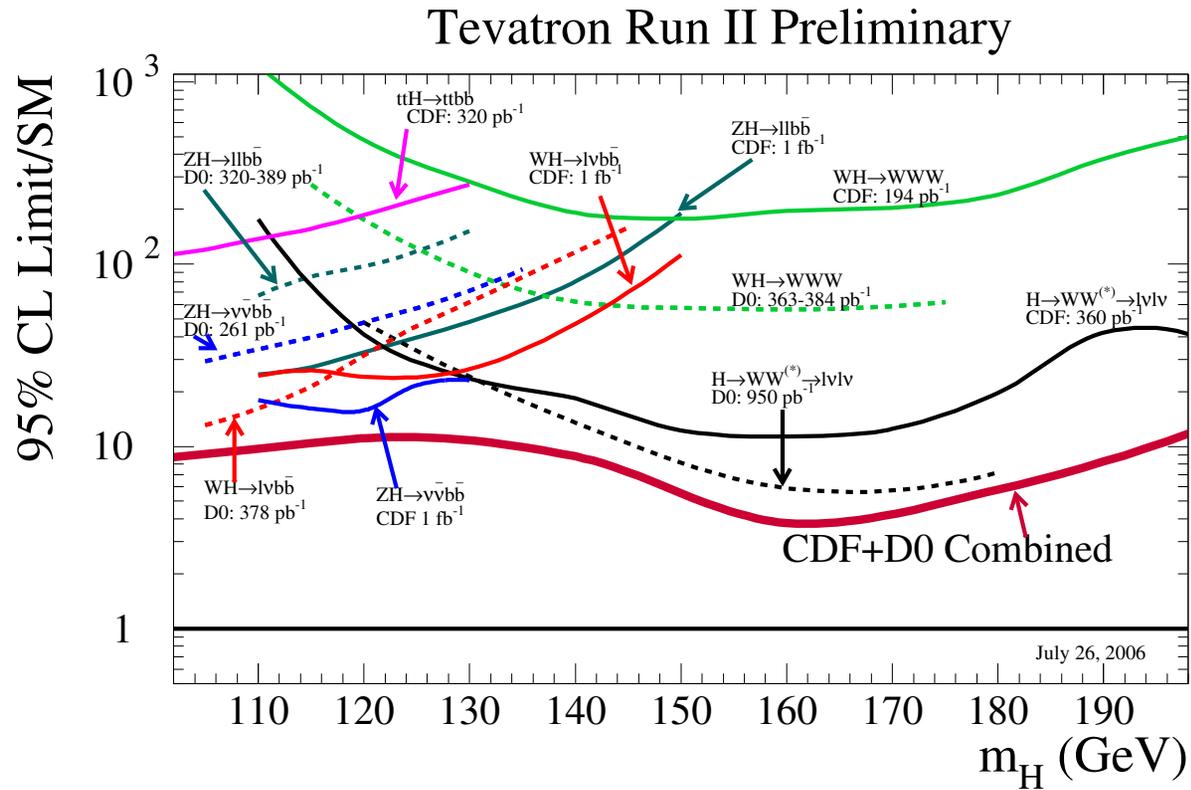
*Effective Luminosity factors gained from various improvements*

Improvement	$WH \rightarrow l\nu bb$	$ZH \rightarrow \nu\nu bb$	$ZH \rightarrow llbb$
NN selection	1.75	1.75	1.0
Mass resolution	1.7	1.7	1.7
Continuous b-tag (NN)	1.5	1.5	1.5
Forward leptons	1.3	1.0	1.6
Track only leptons	1.4	1.0	1.0
Forward b-tag	1.1	1.1	1.1
WH signal in ZH	1.0	2.7	1.0
Product of above	8.9	13.3	7.2
CDF/DØ combination	2.0	2.0	2.0
All combined	17.8	26.6	14.4

Some improvements  
have not yet been  
tackled...

Trigger upgrades needed to maintain efficiency at higher luminosities (tracking upgrade to reduce fakes...)

Necessary to combine results from *many channels* and from *both CDF and DØ* in order to achieve maximum sensitivity



Not yet included

New CDF  $ZH \rightarrow ll\bar{b}\bar{b}$   
 New CDF  $H \rightarrow WW$   
 New DØ  $WH$

→ New results are scaling better than  $1/\sqrt{\mathcal{L}}$

→ Improvements arising mainly from advanced techniques to separate signal from background

*Matrix Element, Neural Net, Boosted Decision Trees...*

## Conclusion and Summary

- Need to take full advantage of the Tevatron and extract as much as we can. → *Probably will never have another  $p\bar{p}$  collider*
- Triggers are still being improved to maintain efficiencies with increasing luminosity → *Smart triggers needed to separate interesting physics from well understood background*
- Understanding background is necessary for new discoveries  
→ *New data is available to tune models and refine predictions*
- Improvements driven by both “doubling statistics and halving systematics” growing faster than  $1/\sqrt{\mathcal{L}}$  → *Exploring new techniques (NN, better  $b$ -tagging, ...), expanding coverage, and collecting more data...*

The Tevatron has a broad and active physics program...

*Precision measurements (QCD, Electroweak...), top properties, single top production, extensive B physics program,  $B_s$  mixing, searches for new physics...*

*Tried to give you a flavor of the challenges we face*

Picked examples from a few of the many interesting results

For more information please visit:

`http://www-cdf.fnal.gov/physics/physics.html`

`http://www-d0.fnal.gov/results/index.html`