Measurement Opportunities at the Tevatron

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TeV4LHC
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Caveats

Drawn from the talks given at the previous TeV4LHC meetings.
I apologize if I fail to adequately cite your material...

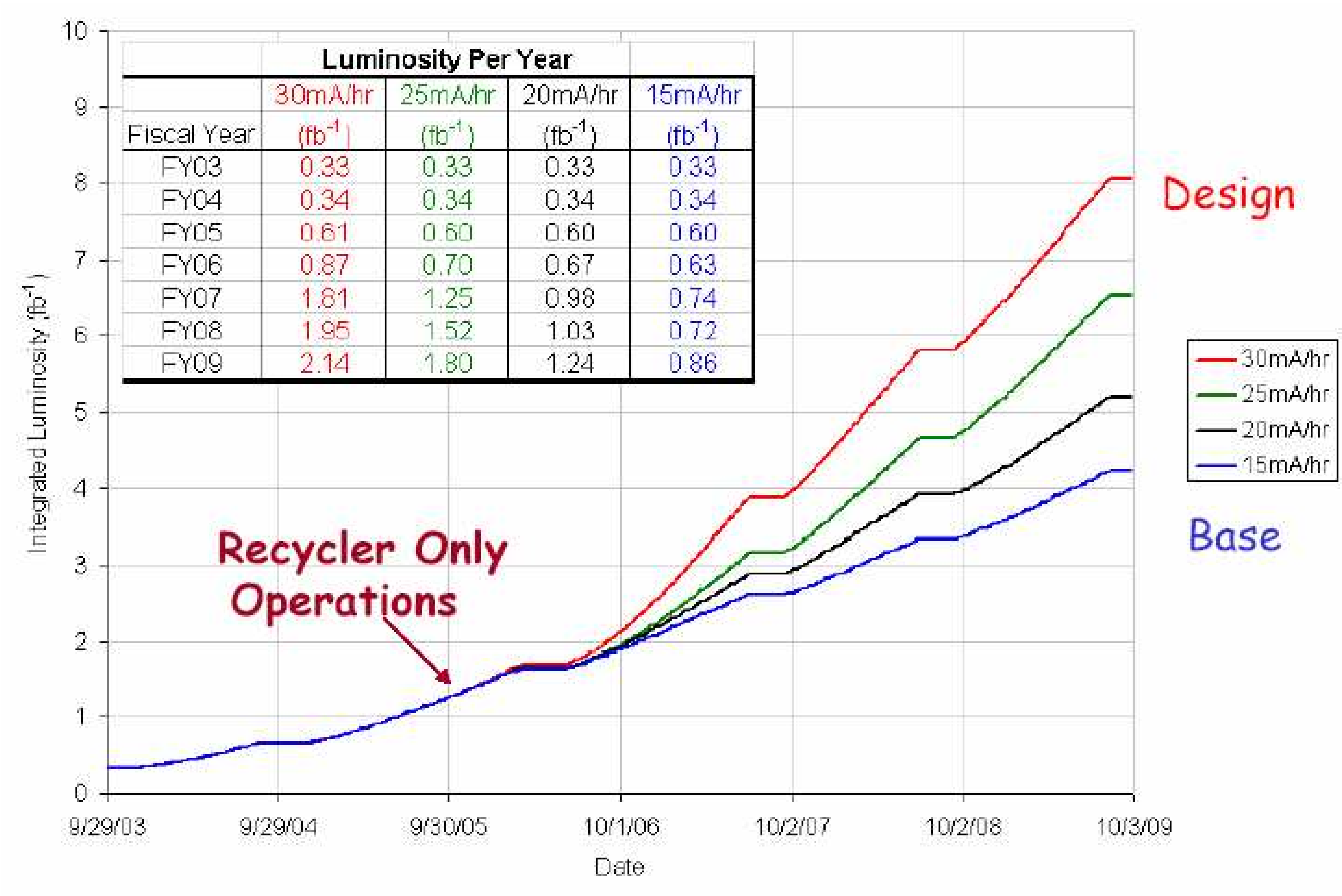
Motivated by the recent Particle Physics Project Prioritization Panel (P5) meetings:

"...for the Tevatron collider, what factors or considerations might lead to stopping operations one year, or two years earlier than now planned? What might lead to running longer than now planned?"

Not attempting to provide a complete list of topics in this talk

Will expand this further in the writeup for the workshop

The Tevatron has delivered more that 1 fb^{-1} of data and is projected to deliver between 4 - 8 fb^{-1} by the end of 2009.



Luminosity Per Year				
	30mA/hr	25mA/hr	20mA/hr	15mA/hr
Fiscal Year	(fb^{-1})	(fb^{-1})	(fb^{-1})	(fb^{-1})
FY03	0.33	0.33	0.33	0.33
FY04	0.34	0.34	0.34	0.34
FY05	0.61	0.60	0.60	0.60
FY06	0.87	0.70	0.67	0.63
FY07	1.81	1.25	0.98	0.74
FY08	1.95	1.52	1.03	0.72
FY09	2.14	1.80	1.24	0.86

Tevatron has been operating well, breaking records, and has delivered more that 5 pb^{-1} during a single store (more than once).

To put this in context, the LHC is expected to have accumulated from 0.1–10 fb^{-1} of data by the end of operations in **2008**.

"What are the advantages of running the Tevatron until the end of 2008 (2009) and accumulating 6(8) fb^{-1} before the LHC has a comparable amount of data?"

One goal for Run II should be the establishment of a "complete" description of Standard Model backgrounds to new physics.

$\longrightarrow$ *To expand beyond our current knowledge, this means obtaining a good understanding of the single top and diboson production processes and an excellent understanding of the $t\bar{t}$ process.*

$\longrightarrow$ *Extract as much information from the Tevatron as we can in order to reduce uncertainties on PDFs*

$\longrightarrow$ *Understand background processes to new physics*

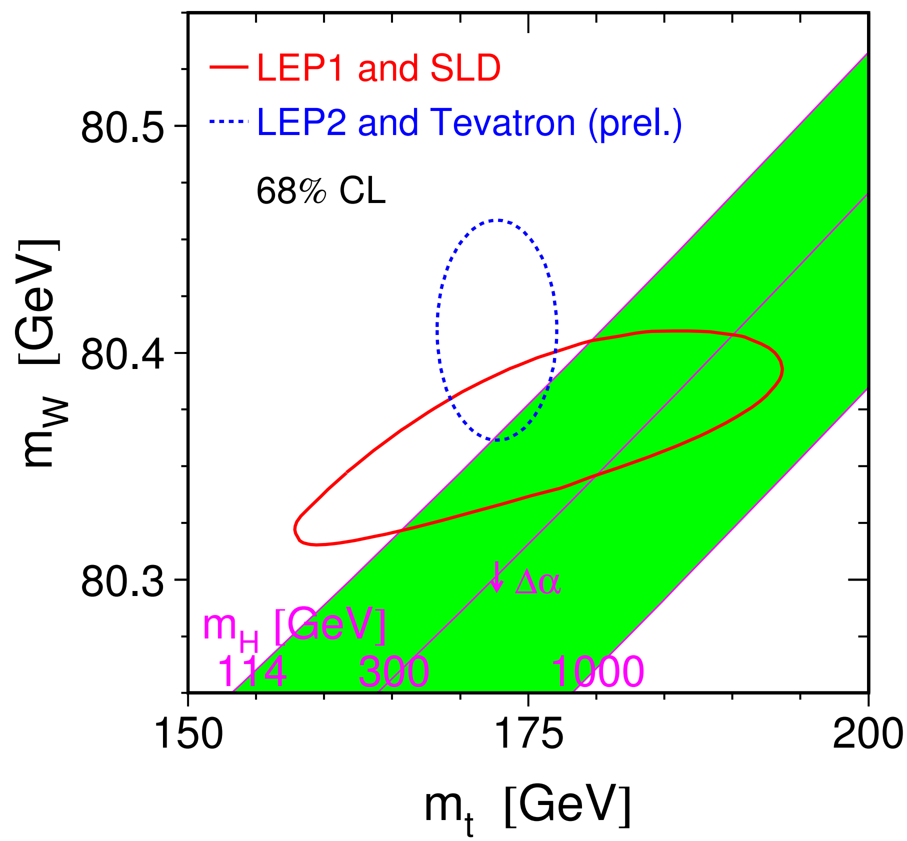
$\longrightarrow$ *Tune MC generators in preparation for LHC*

The Tevatron has unique attributes *complementing* existing and future experiments which need to be fully exploited

1. *Unique energy (2 TeV) and energy range (≤ 2 TeV)*
2. $p\bar{p}$ *(vs* pp*) (larger* $m^2/\sqrt{s}$*,* $q\bar{q}$ *diagrams, CP tests)*
3. *Valence quark interactions*
4. *Fewer extra collisions for searches for rare exclusive processes vetoing jets e.g. rapidity gaps, VBF processes, exclusive ED-searches (*γ*-MET e.g.)*
5. *Fewer extra jets and photons from multiple collisions in searches for complex events with soft jets and/or photons*
6. *Well understood detector, mature software tools and expertise in analysis*

Precision Electroweak Measurements

A key test of the Standard Model, once we have a Higgs mass, is to look for consistency between the W, Top and Higgs mass.



In order to constrain the SM Higgs mass need to measure both m_W and m_t

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

LEP EW WG web pages

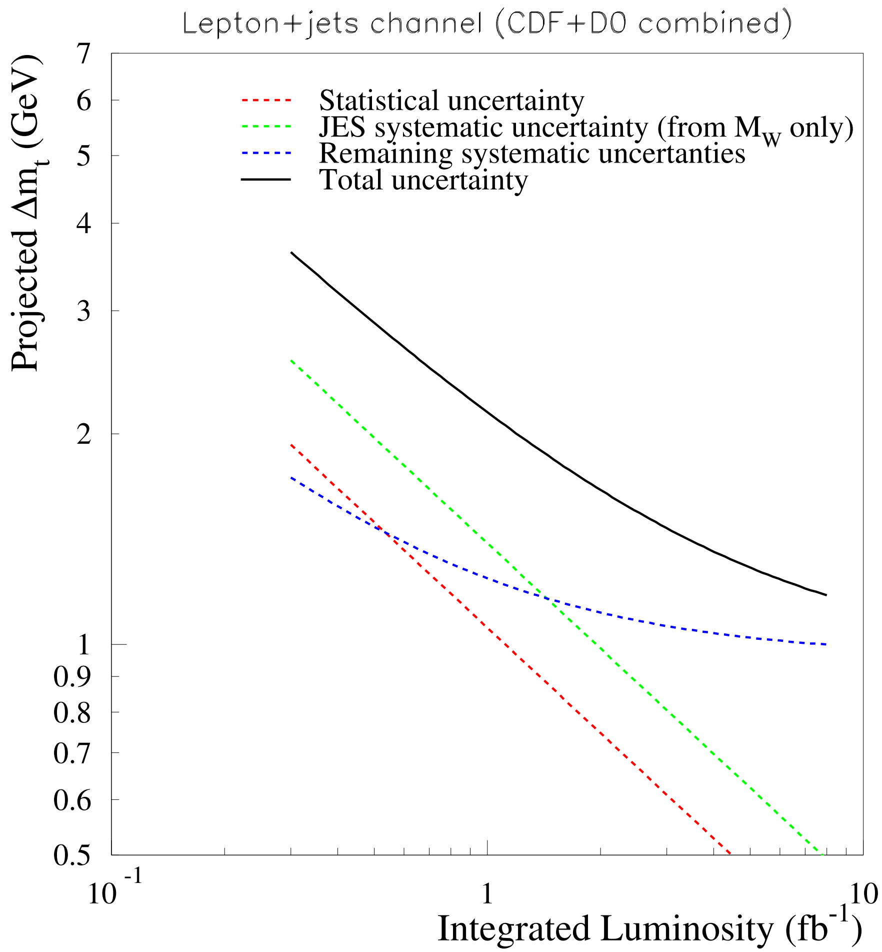
Top Mass Measurement: $\delta m_t \sim 1.5$ GeV

Uncertainties that scale with luminosity - $1/\sqrt{\mathcal{L}}$

- Statistical uncertainty normalized at $\mathcal{L} = 318$ pb^{-1} to performance of current analyses.
- Uncertainty due to Jet energy scale - in situ determination using $W(\rightarrow 2$ jets) mass.

Uncertainties that do not scale with luminosity

- PDFs, initial and final state radiation, b-jet energy scale, b-tagging, background modeling



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

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

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

LHC predicts 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...

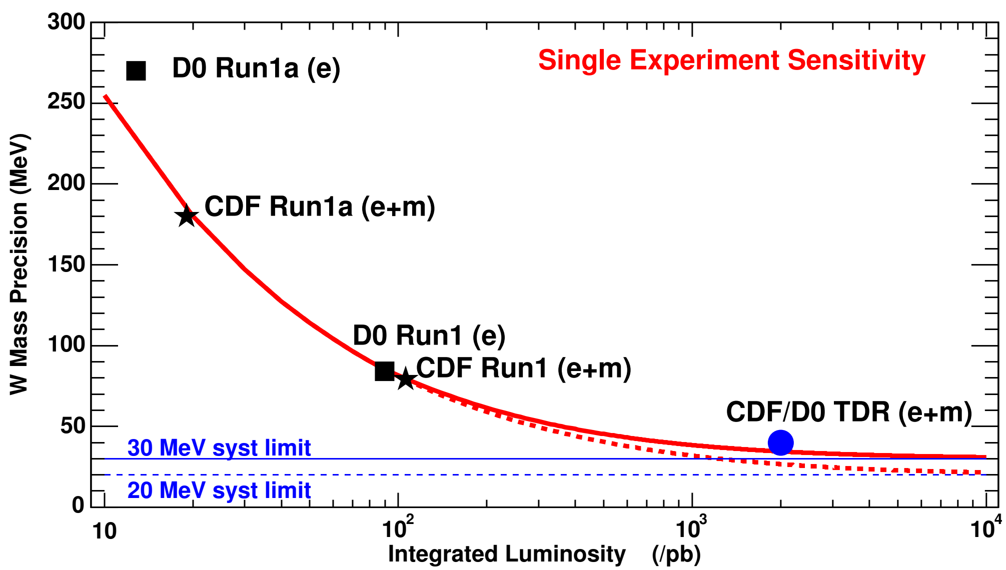
W mass measurement: $\delta m_W \sim 20 - 30$ MeV

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:

$\delta m_W \sim 10 - 20$ MeV

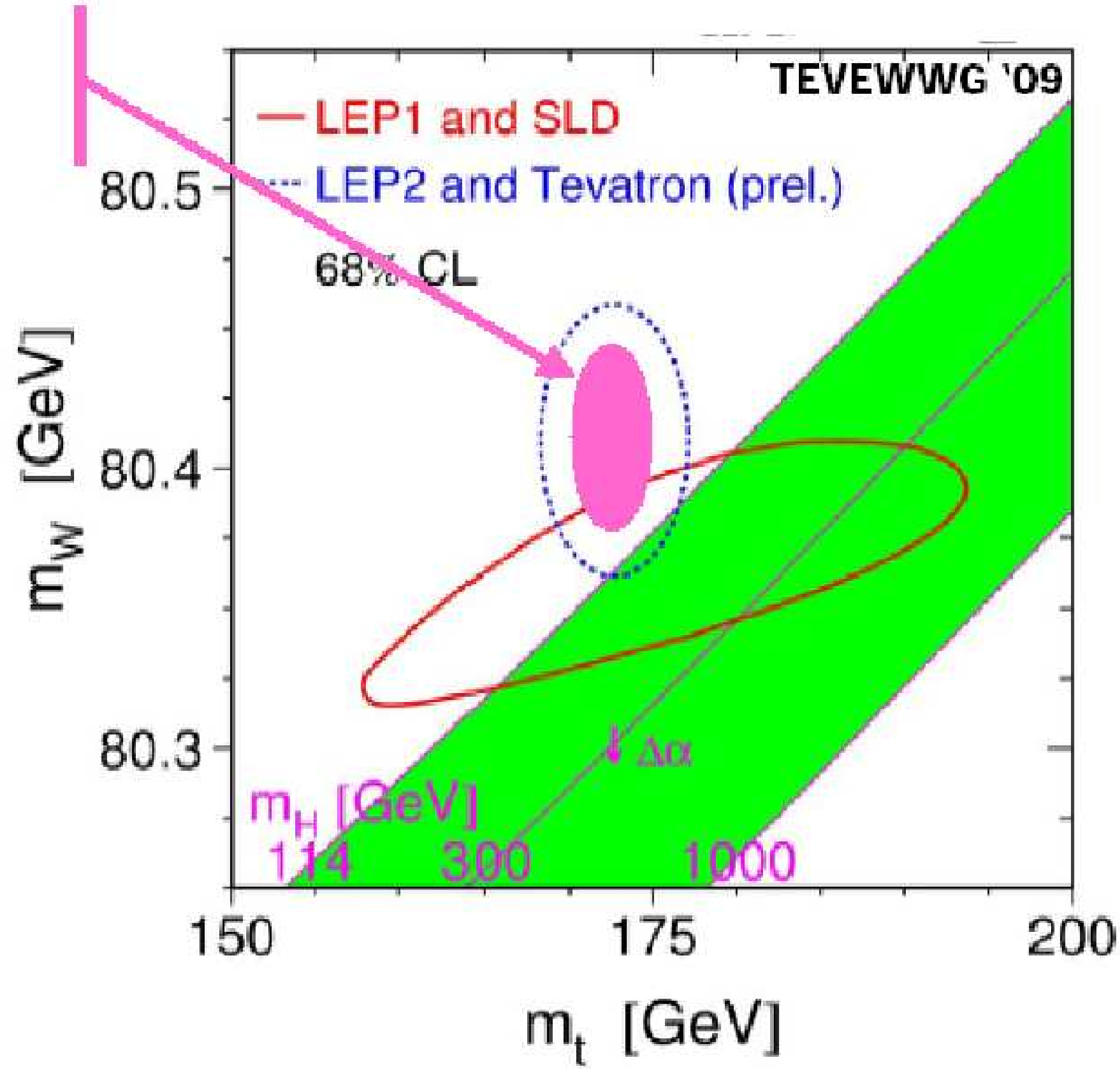
Requires:

→ *low luminosity running*

→ *good understanding of the detector*

Prospects from reducing the errors on m_t and m_W

$\delta m_t = 1.2$ GeV
$\delta m_W = 24$ MeV

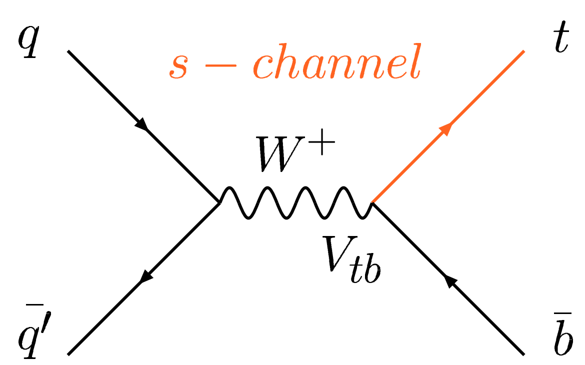


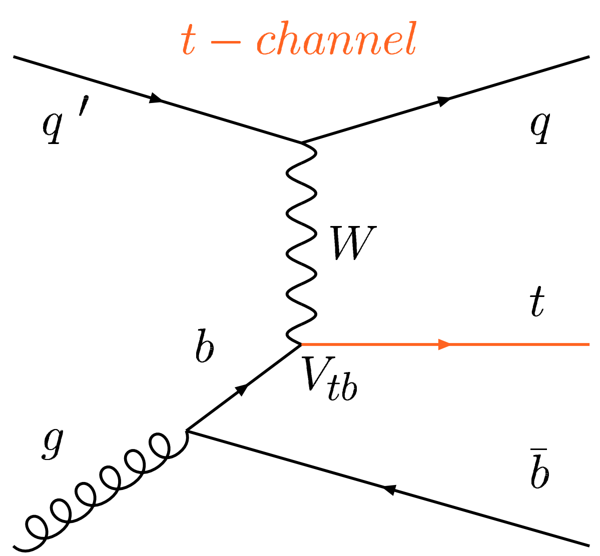
→ Provides tighter constraints on the SM Higgs

→ Could be available near the start of LHC physics running

J. Hobbs, presentation to P5

Single top production





→ *Tests the SM, search for new physics*

→ *Important to fully understand top production (probes V_{tb})*

→ *Important for Higgs searches*

→ *Probes the heavy flavor content of the proton*

SM Predictions:

σ(s − channel) = 0.88 ± 0.14 pb

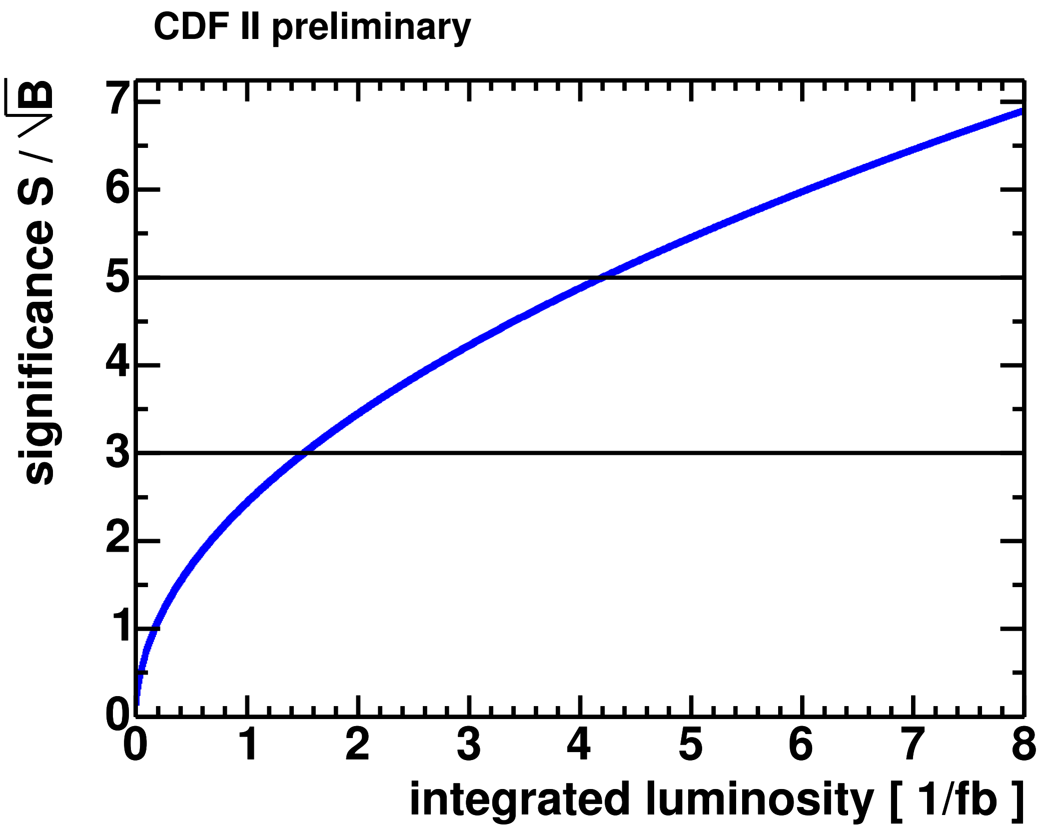
σ(t − channel) = 1.98 ± 0.30 pb

Currently published bounds:

s-channel: $\sigma < 6.4$pb

(DØ 230 pb^{-1})

t-channel: $\sigma < 5.0$pb



Combined channel likelihood for SM single top production.

With 4 fb^{-1} (2007/8?), we expect an event sample of about 75 events and should have a 5 σ signal to claim discovery.

If the measurement is statistically limited, then the total production cross section will be known to roughly 10%.

A doubling or quadrupling of the data will easily allow for multivariate fits, increasing our confidence that we are observing pure Standard Model single top production.

Di-Boson Production

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

ZZ/ZW production probes the triple guage boson couplings.

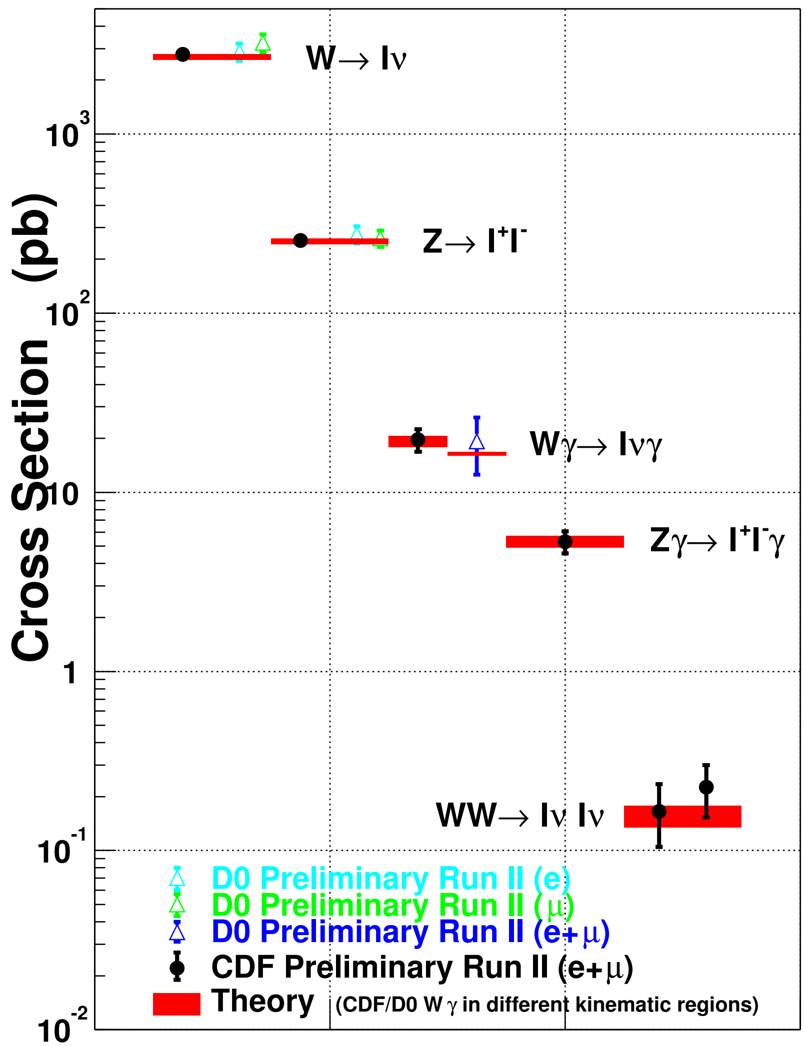
$\rightarrow$ *The presence of unexpected neutral triple-guage-boson couplings (*ZZZ *and* $ZZ\gamma$*) can lead to enhanced* ZZ *production.*

$\rightarrow$ *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.

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

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



hep-ex/0405026

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

With 194 pb^{-1} of data CDF set a 95% confidence level upper limit of 15.2 pb on the cross section for ZZ plus ZW production, compared to the standard model prediction of 5.0 ± 0.4pb (hep-ex/0501021).

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

With more data, Di-Boson measurements could soon become "precision measurements"...

Details of 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. The UE contains particles that originated from initial and final state radiation, beam-beam remnants, and multiple parton interactions.

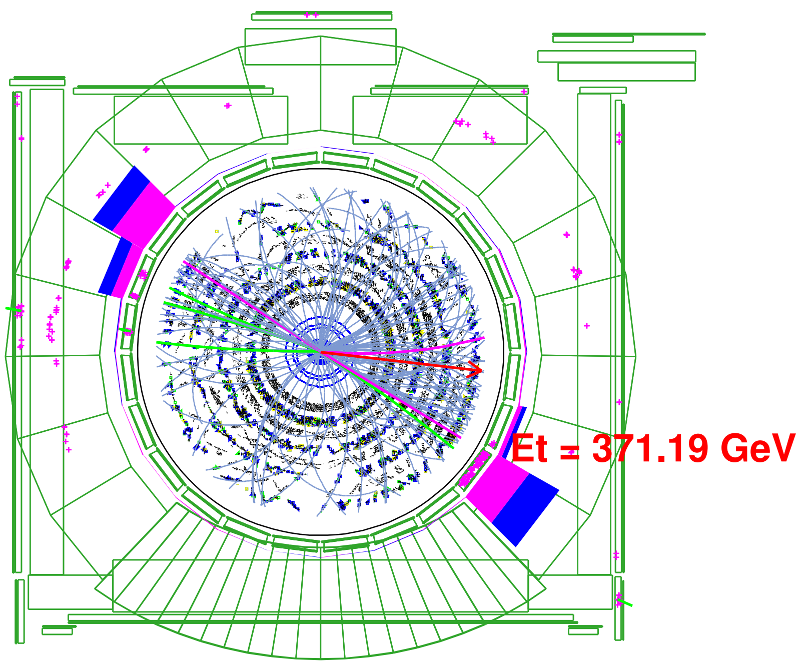
$\longrightarrow$ *Measure the cross-section for multiple-parton collisions and establish precisely how much it contributes to the UE in various processes.*

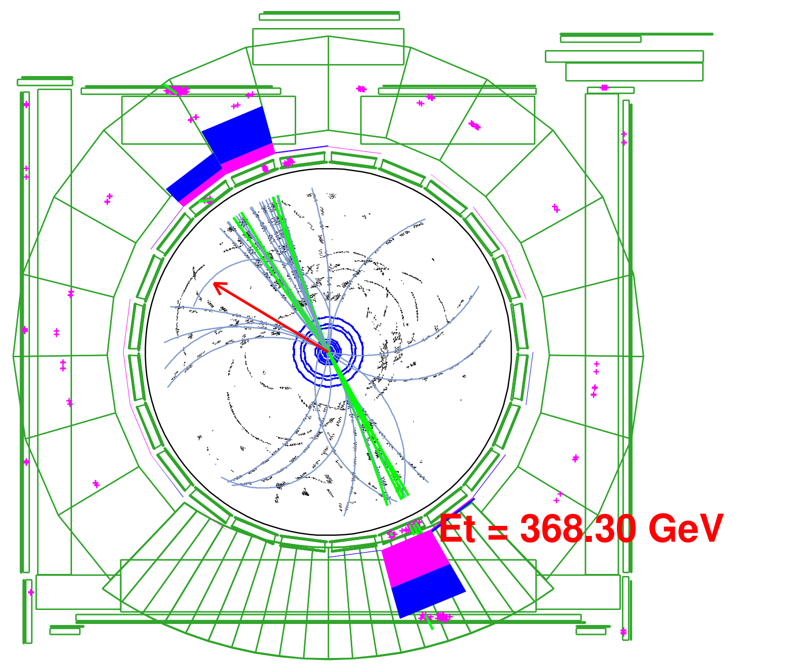
$\longrightarrow$ *Study the UE in color singlet production (Z-boson and Drell Yan processes).*

$\longrightarrow$ *The UE in color singlet production can be compared to the UE in high p_T jet production. Forward detectors can be used to extend measurements to large rapidity.*

→ Multiplicity distributions in W, Z, Drell Yan, WW, ZZ, and WZ would be very interesting.

→ Establish the rate of vector boson fusion (VBF) and study the probability of rapidity gaps.



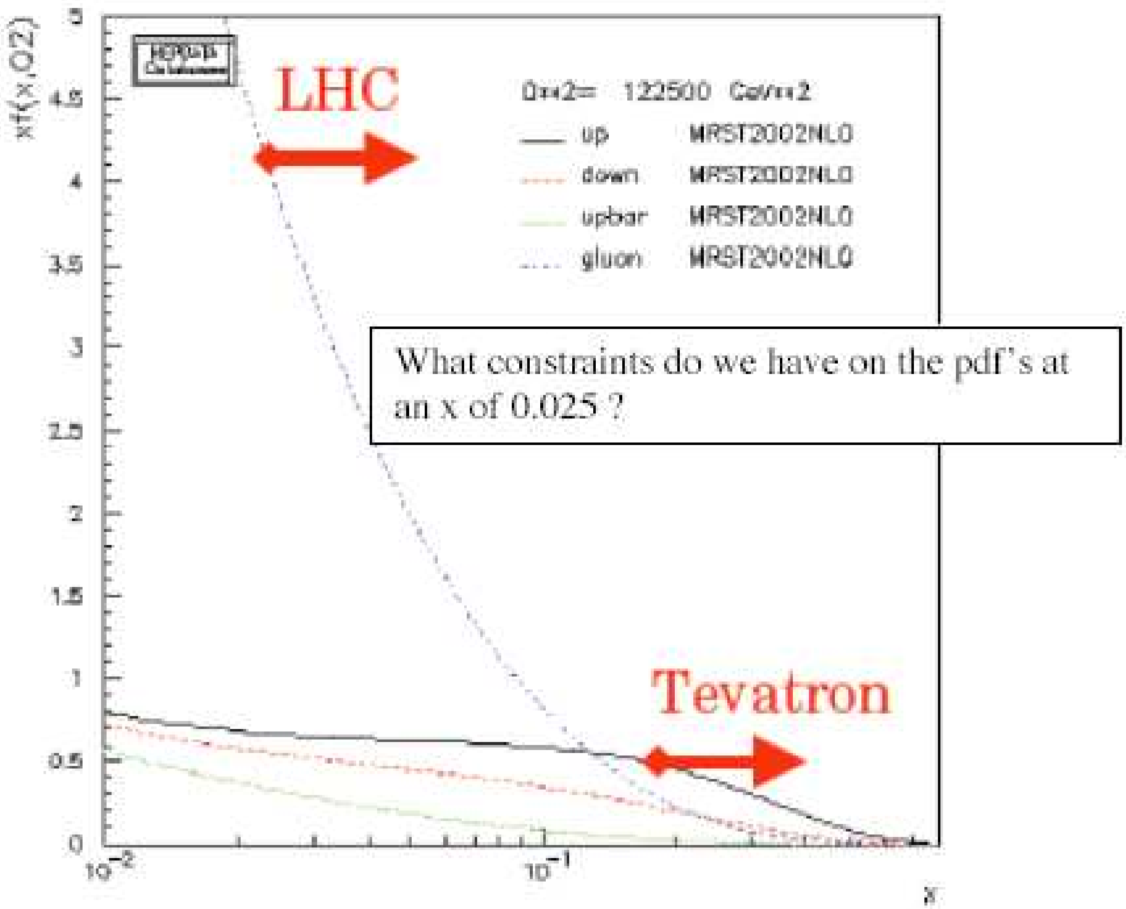


An understanding of the UE will be among the first things that will be needed at the LHC...

Can we find "universal tunes"... HERA → Tevatron → LHC

Tevatron and LHC (will) access different kinematic regions

→ *Tevatron valence quark dominated*
→ *LHC sea quark dominated*



An important aspect of the Tevatron program is to provide data that can be used in new global QCD fits to produce refined sets of PDFs with reduced uncertainties.

PDF Uncertainties

Errors on PDFs can influence the measurement at several stages

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

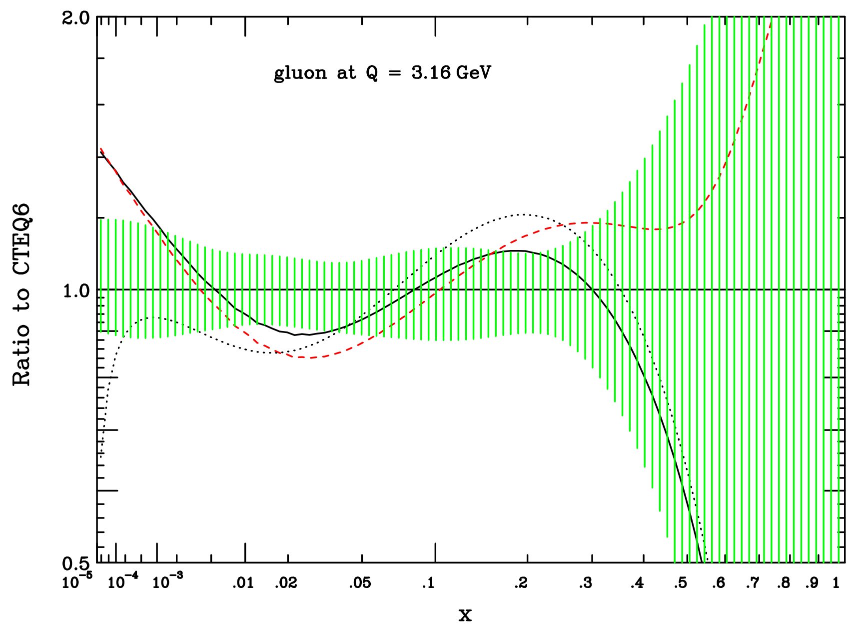
Calculation of acceptance (ϵ), luminosity ($\mathcal{L}$), event selection (N_{obs}), background estimate (N_{bkg})

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

Theory calculation includes:

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

Input to PDFs - What is Unknown



hep-ph/0201195

Gluon distribution

$\longrightarrow$ *Inclusive jet, forward jets*

Shaded band shows the CTEQ6 gluon uncertainty at $Q^2 = 10$ GeV^2

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

Strange and anti-strange quarks, strange asymmetry

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

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

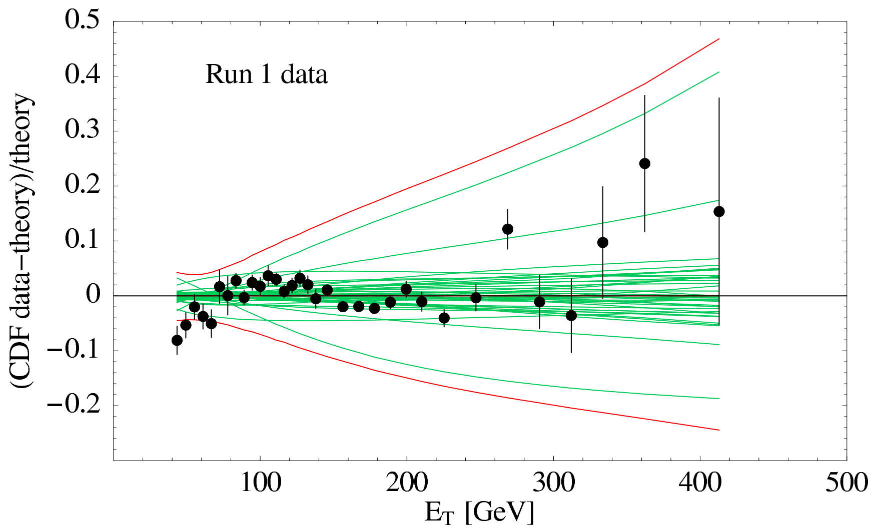
$\longrightarrow$ W *charge asymmetry*

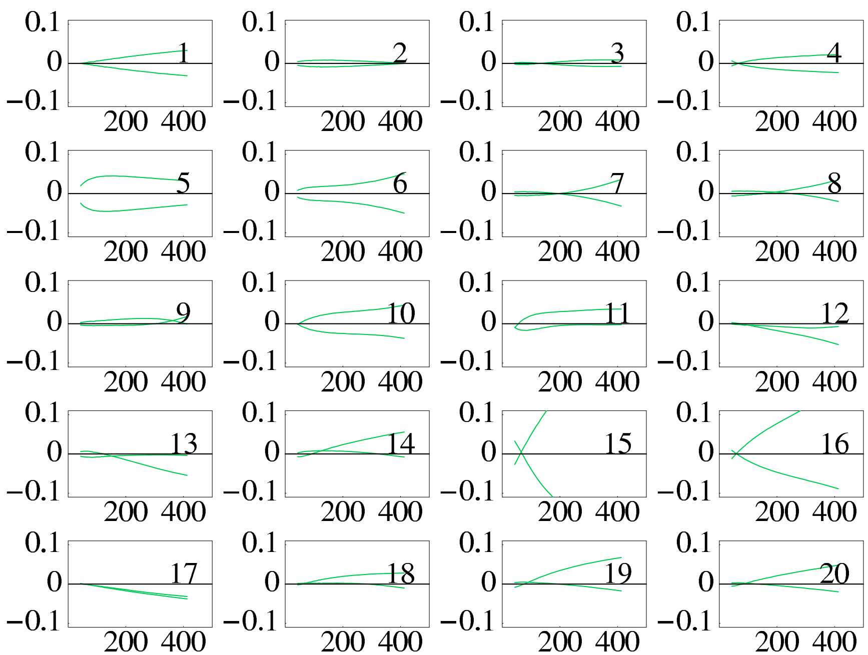
$\longrightarrow$ W *rapidity distribution*

Heavy quark distribution

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

Run I Inclusive Jet Cross Section





Cross section is calculated using the central PDF and for each error PDF, errors added in quadrature $\Delta\sigma^{\pm} = \sqrt{\sum_i \sigma_i^{\pm\,2}}$

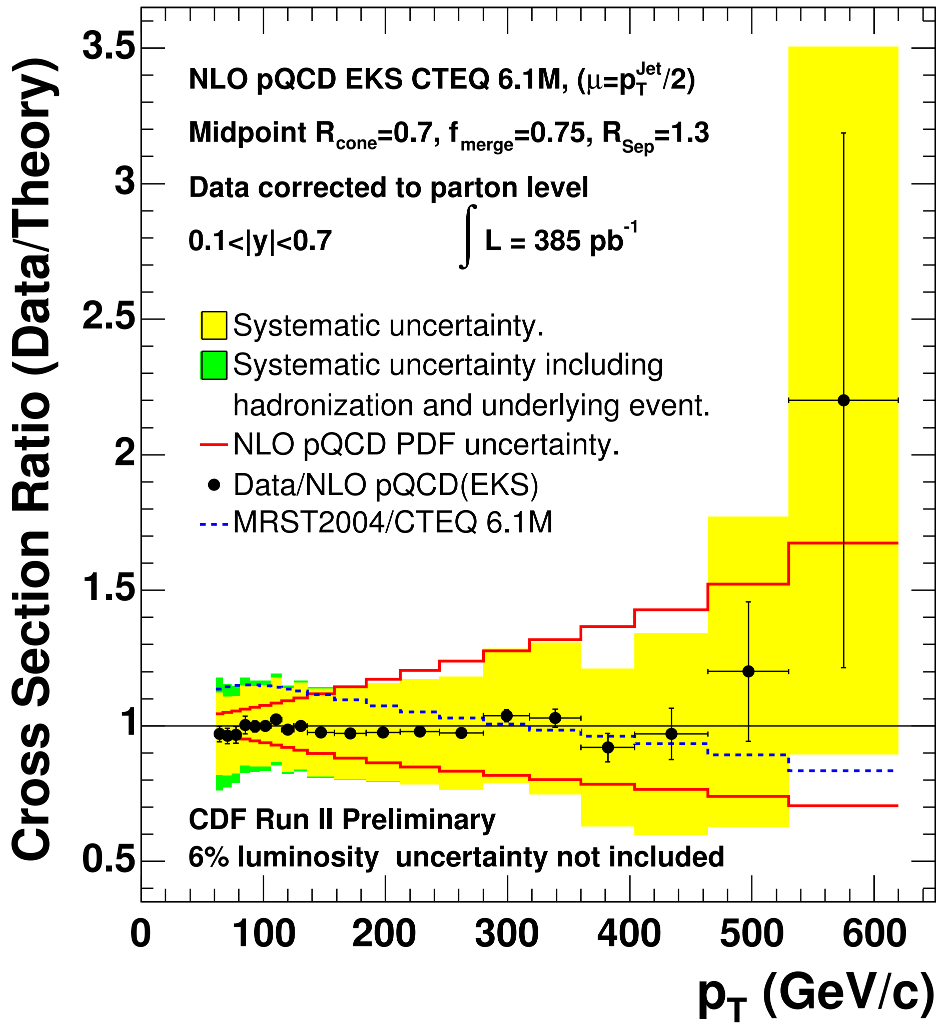
40 sets for CTEQ, 30 for MRST

Largest contribution to the uncertainty comes from eigenvector 15

Related to high x gluon behavior

hep-ph/0303013

Increased center-of-mass energy (1.8 → 1.96 TeV) yields a larger cross section at high E_T ~ 2× *at 400 GeV and* 5× *at 600 GeV*



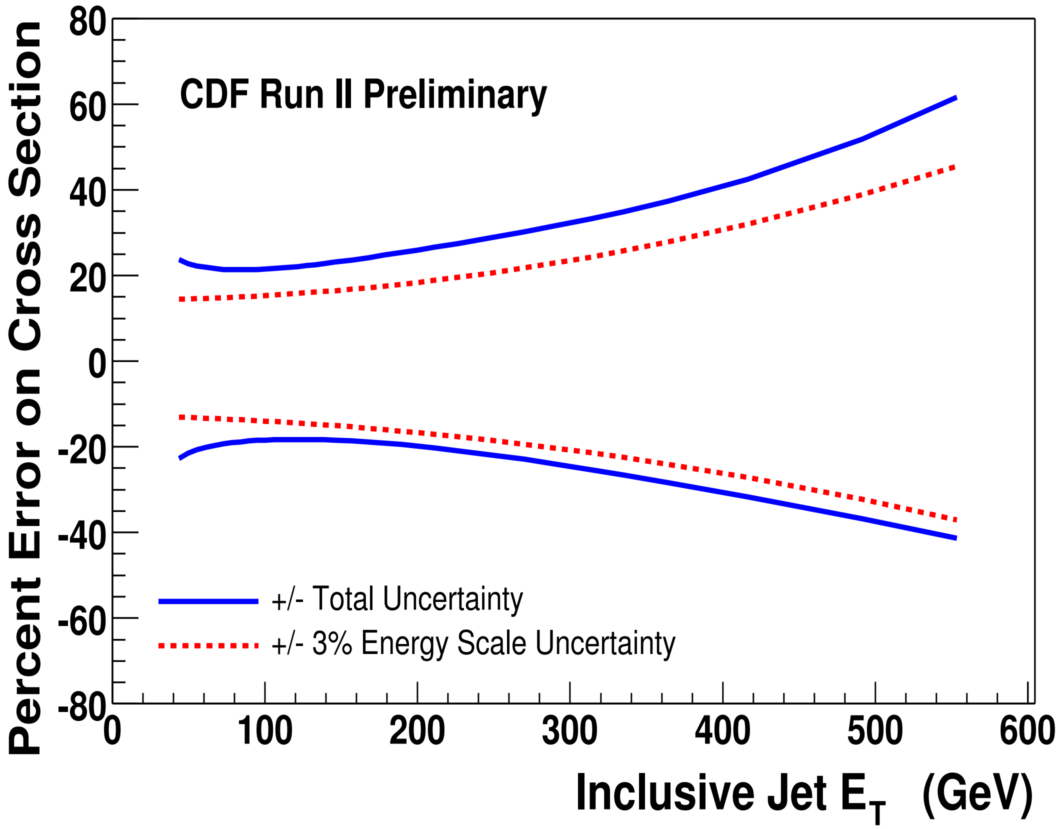
Latest CDF Run II results using the cone based jet algorithm, MidPoint *(first public appearance...).*

Results based on 385 pb^{-1}

Extends Run I results by ~ 150 GeV

New data will provide tighter constraints on PDFs, in particular the high x gluon distribution

Uncertainty in the energy scale is the dominant source of systematic error, challenging to improve this...



The effect of a 3% energy scale uncertainty (dashed line) contribution to the total systematic error (solid line)

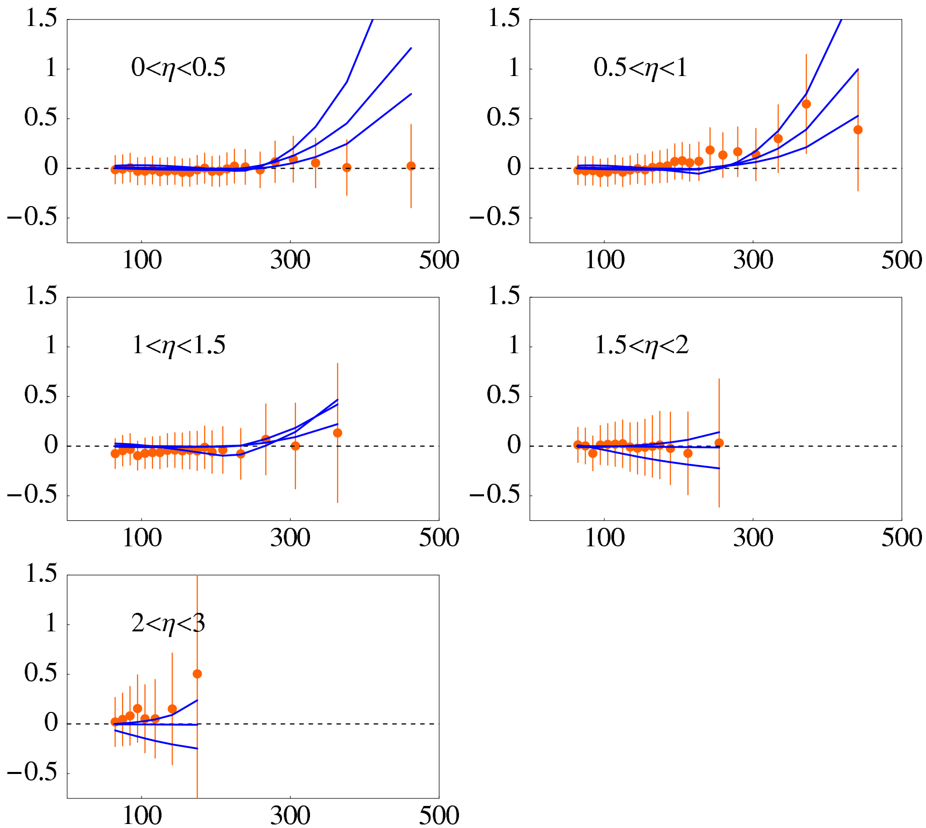
Uncertainty on the cross section due to the energy scale gets larger in the forward region because of the faster falling spectrum

May be able to reduce systematic uncertainties by measuring ratios (inclusive: forward/central, dijet: SS/OS...)

New Physics could show up as a deviation from the SM predictions at high E_T in the inclusive jet cross section.

Flexibility in the PDF parameterizations could accommodate deviations in the central inclusive jet cross section at high E_T

Run I DØ data, inclusive jet cross section binned in rapidity (last bin $2 < |\eta| < 3$)

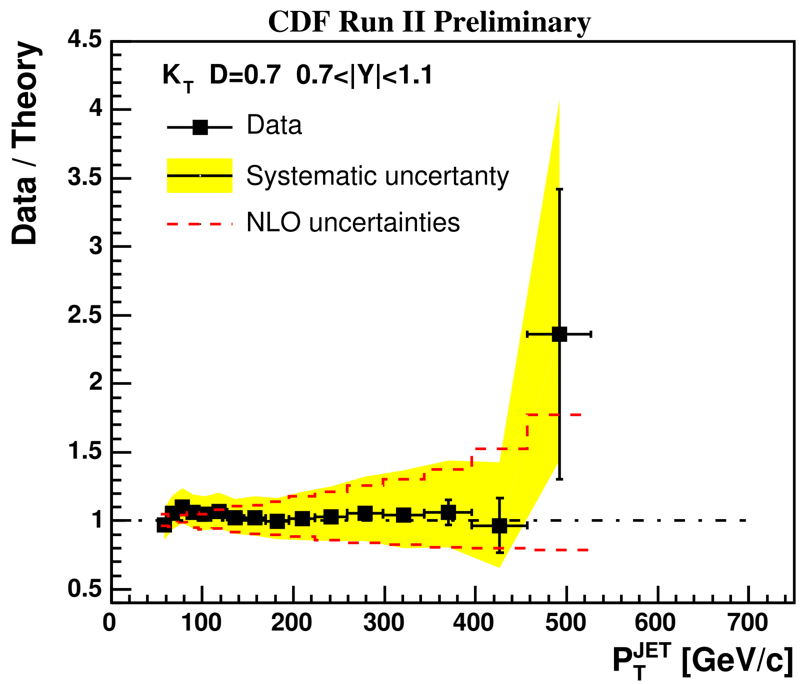


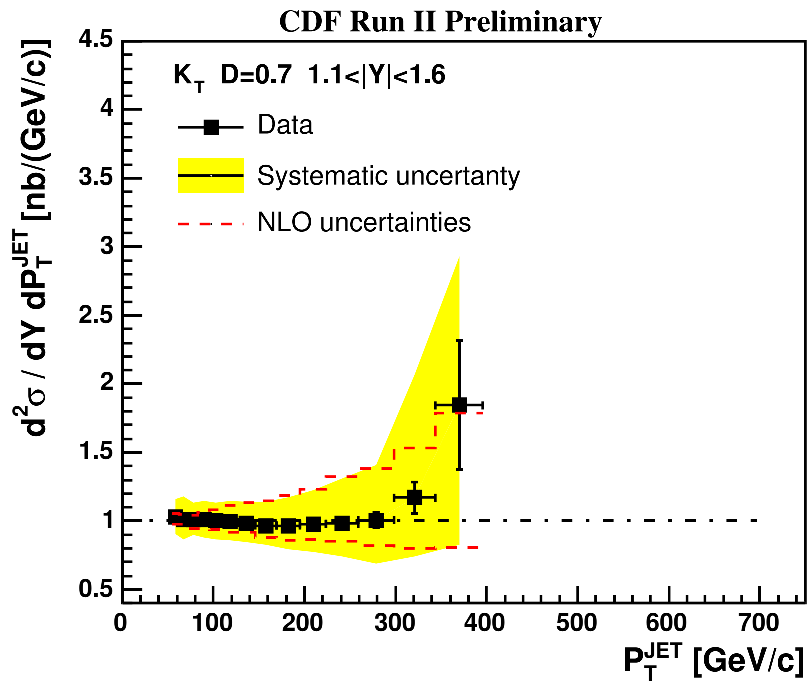
Usually look at the angular distribution between two leading jets

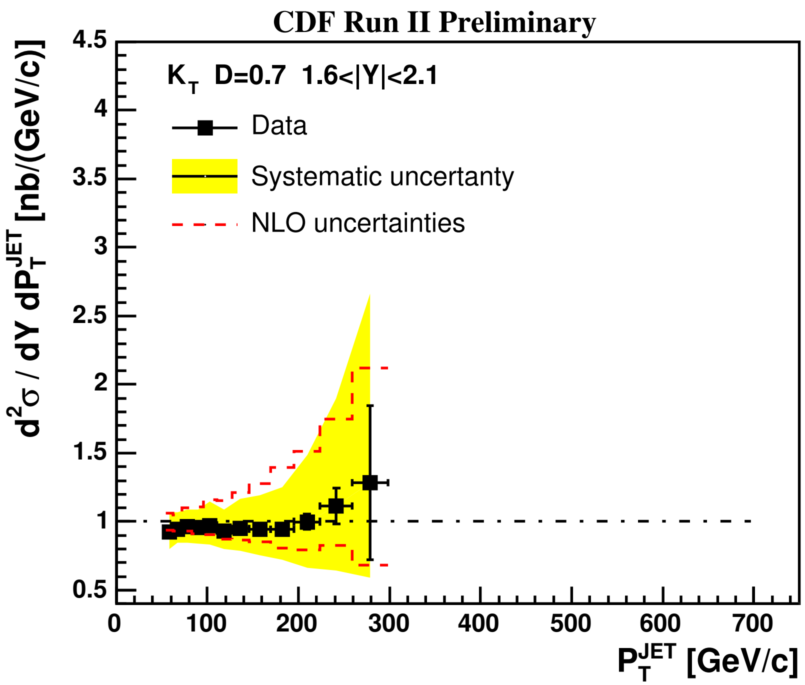
More general to include forward jets in the global fit

Curves show the result of a global fit including a contact interaction in theory with $\Lambda = 1.6, 2.0, 2.4$ TeV

Stump et al., hep-ph/0303013







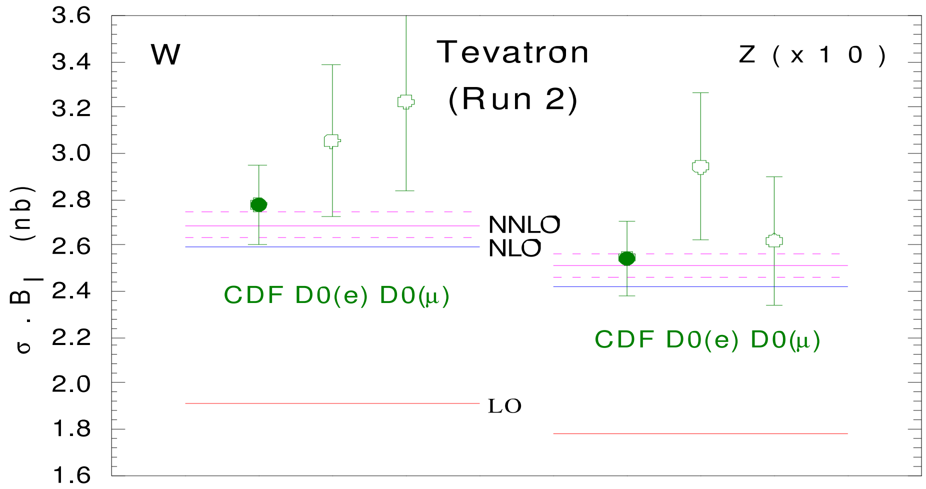
CDF Run II Preliminary results based on 385 pb^{-1} of data.

Forward ($|y| < 2.1$) Jet Data using the k_T Clustering algorithm

W/Z Cross Sections

"Standard Candle" process that can be used to determine the proton-proton luminosity at the LHC

High statistics, theoretically well understood and well measured



$\sigma_{\text{NLO}}(W)$ at the LHC

MRST2002	204 ± 4 (nb)
CTEQ6	205 ± 8 (nb)
Alekhin02	215 ± 6 (nb)

$\rightarrow$ 2-4% uncertainty

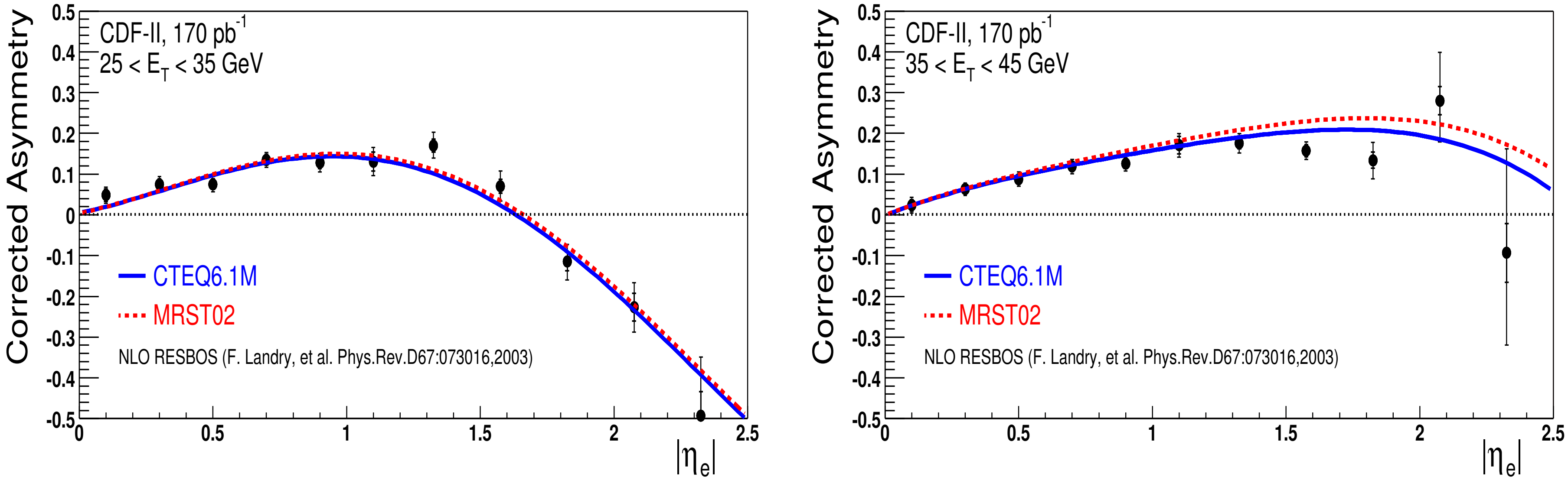
Different PDF sets lead to different predictions...

Choice of $\Delta\chi^2$ definition leads to different error on calculation...

Can use cross section ratios to reduce the uncertainty on the luminosity to $\sim$ 1% (Dittmar et al., hep-ex/9705004)

W Charge Asymmetry

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



hep-ex/0501023

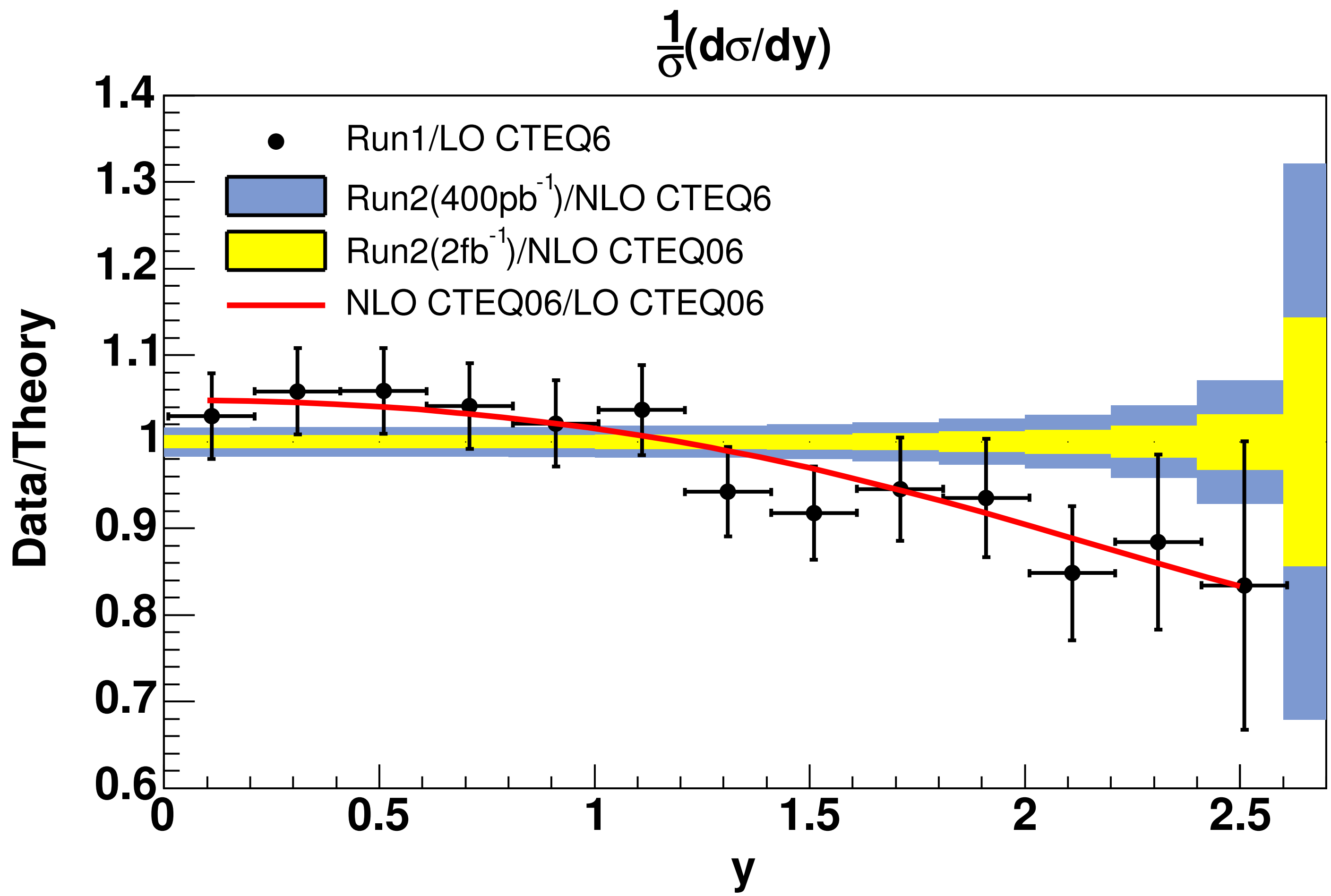
In Run II we now have two E_T^e bins
$\longrightarrow$ now able to explore the E_T^e dependence

Differences start showing up at high rapidities...

In general for global QCD fits it is better to have differential distributions (more bins in η, E_T^e)...

Z Rapidity Distributions

The shaded bands show the expected reduction in the statistical error for 400pb^{-1} and for 2fb^{-1}



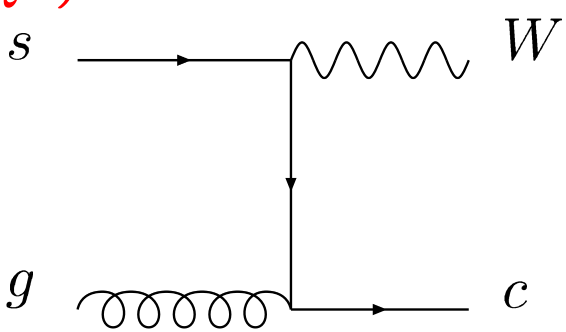
Currently not being used in fits... but may be promising

Intrinsic Heavy Quark

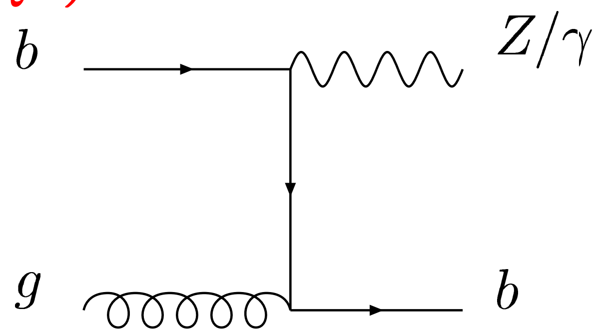
Very little direct experimental input → *all c and b distributions in existing PDF sets are radiatively generated*

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

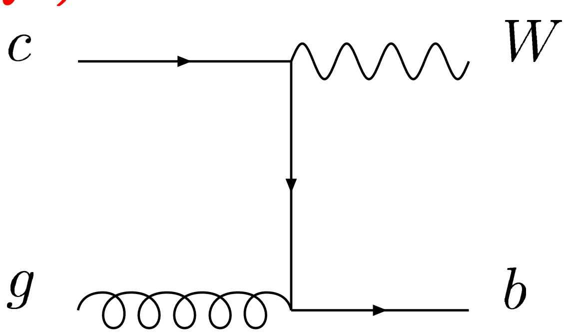
$s(x, Q^2)$

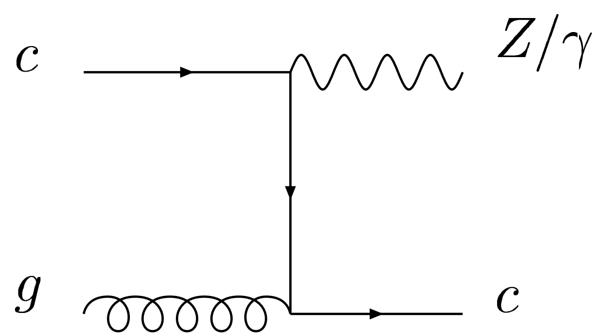


$b(x, Q^2)$

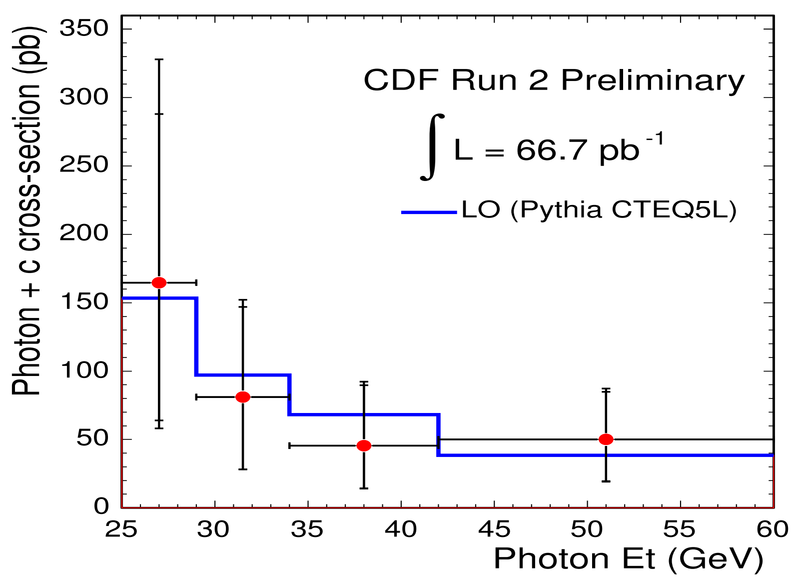


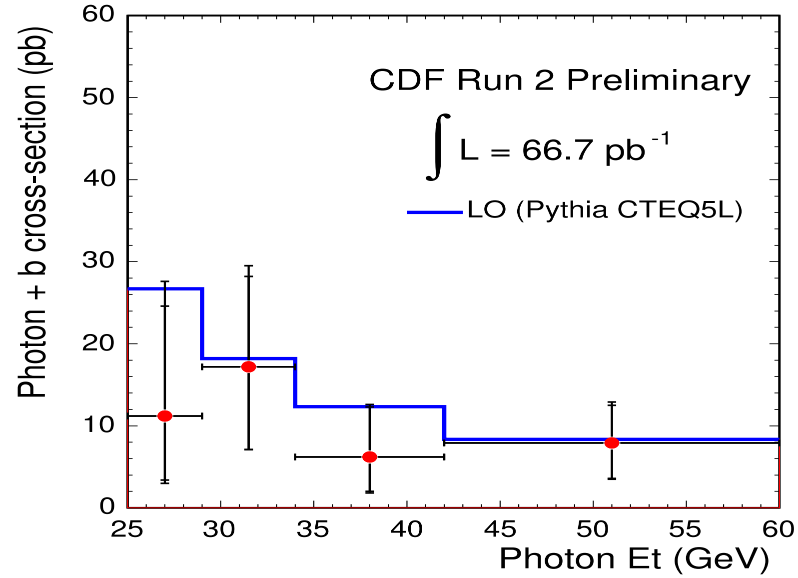
$c(x, Q^2)$





γ plus Tagged Heavy Flavor





Dominated by statistical errors

Largest systematic errors

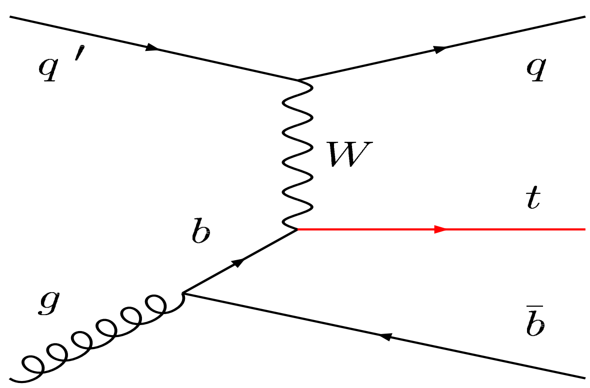
$\longrightarrow$ *Energy scale*

$\longrightarrow$ *Tagging Efficiency*

$\longrightarrow$ *Trigger*

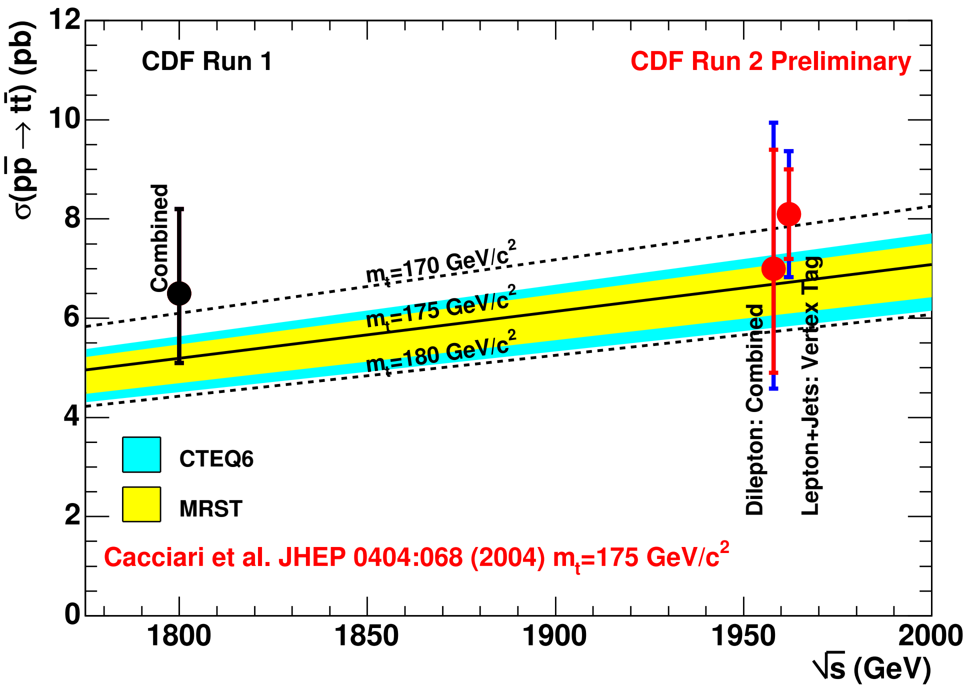
Can we constrain intrinsic heavy flavor at the Tevatron?

Single top production also probes b quarks at high x



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

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

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

→ Dominated by PDF and α_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...*

Higgs Cross Section

Cross section uncertainty calculated for main production processes of the SM Higgs (*Djouadi and Ferrag hep-ph/0310209)*

$q\bar{q} \to VH$	associate production with W/Z
$qq \to Hqq$	massive vector boson fusion
$gg \to H$	gluon fusion
$gg, q\bar{q} \to t\bar{t}H$	associate production with top quarks

Get very different results when using different PDF sets:

$\longrightarrow$ *Choice of data used as input to fits*

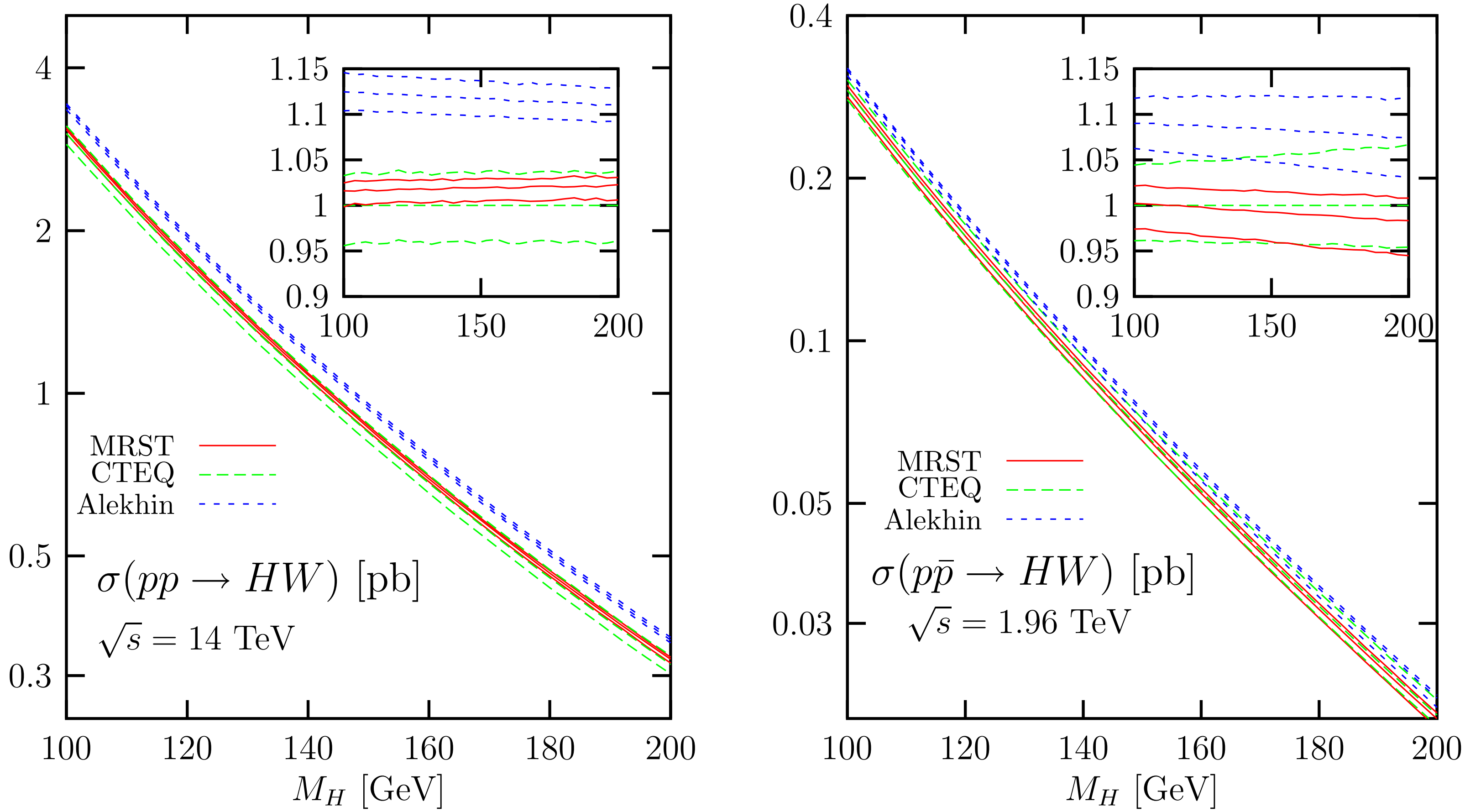
$\longrightarrow$ *Treatment of errors*

$\longrightarrow$ *Parameterization of parton distributions*

$\sim 15\%$ spread between PDF sets at Tevatron and LHC energies

$\sim 5\%$ uncertainty for a given PDF

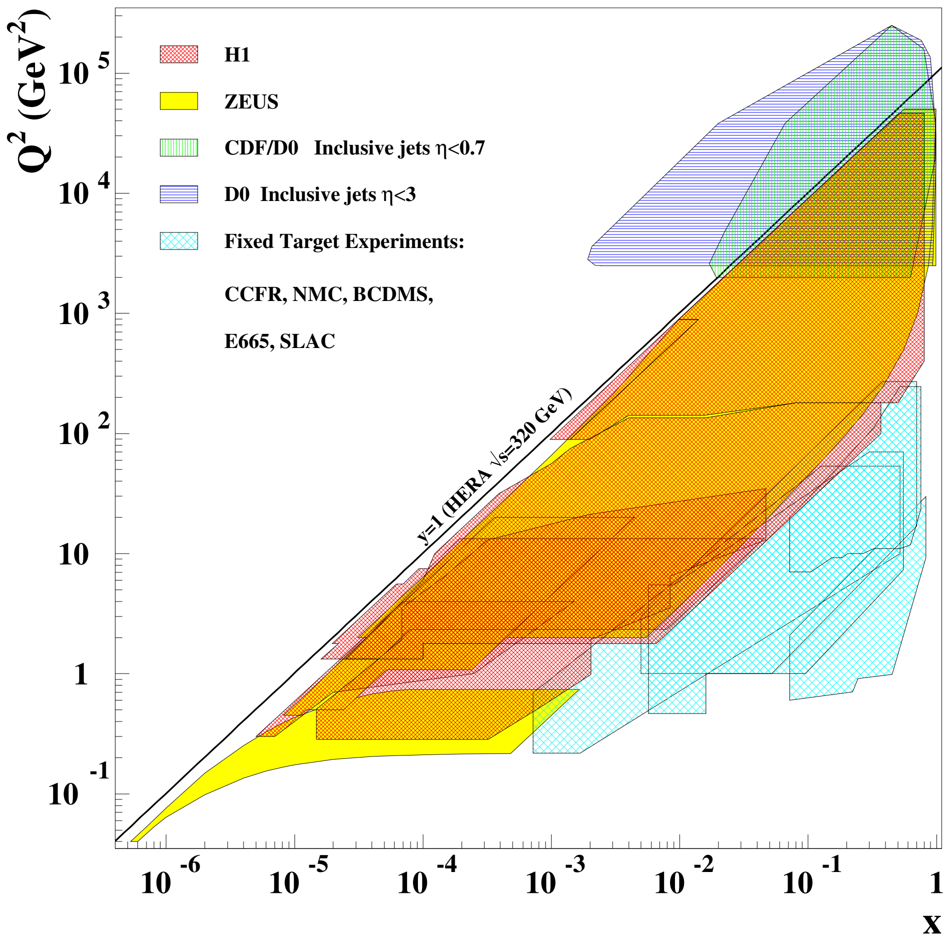
Large error arises from the uncertainty of the gluons



Djouadi and Ferrag hep-ph/0310209

$\rightarrow$ *For a discovery it is important to have a precise understanding of the backgrounds...*

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*

→ *Try to span the kinematic phase space*

The challenge is to demonstrate consistency between measurements in different regions of phase space as well as between different processes

Almost Finished...

Need to take full advantage of the Tevatron and extract as much as we can. $\rightarrow$ *Probably will never have another $p\bar{p}$ collider*

In addition to the usual arguments

- Searches for new physics
- Precision electron weak measurements (m_t, m_W)
- Single top production
- B_s mixing
- $\Delta\Gamma_s/\Gamma_s$

There are other basic measurements that we should not ignore

- Better understanding of $t\bar{t}$ production
- Di-Boson production
- Heavy flavor PDFs
- Heavy flavor splitting probability
- Jet reconstruction at high rapidity
- b tagging efficiencies

- τ reconstruction efficiencies
- Studies of rapidity gaps
- Details of the underlying event
- Transition between perterbative and nonperterbative QCD
- Improved PDFs
- Vector boson production and tests of QCD
- W charge asymmetry
- Jet fragmentation
- ISR/FSR
- ...

As part of the write up for this workshop we would like to highlight these measurements. *Have this handy when someone asks "why should we continue Tevatron operations..."*

Your input and suggestions are welcome, *please send them to:*

`chlebana@fnal.gov`

Can imagine that analysis on Tevatron data continues after operations stops
$\longrightarrow$ *plenty of data for theses topics*
$\longrightarrow$ *need to make sure that the data remains accessible*

Summary

• With more data we can expect improved measurements which will be *competitive and complimentary* to those at the LHC.

• Take advantage of uniqueness of the Tevatron and ensure that "key" measurements are identified and get done...
$\longrightarrow$ *This workshop is an excellent forum to do so...*

• With a bit more data we will be in a position to observe some important SM processes and study them in detail...

• PDF uncertainties creep up in a number of places: *acceptance, luminosity, background estimates, comparison to theory...*

• Uncertainty of the gluon at high x results in the dominant error on many interesting measurements, *use the inclusive jets measurements to pin this down*

• Make full use of Run II Tevatron data to refine PDF sets and reduce the associated uncertainties.