Precision Measurements at Hadron Colliders

C.-P. Yuan

Michigan State University
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I thank my collaborators for providing many useful slides. Special thanks to Chuan-Ren Chen, Qing-Hong Cao, Hong-Liang Lai, Pavel Nadolsky, and Wu-Ki Tung.
By comparing measurements and theoretical prediction of electroweak precision observables:

- the electroweak sector of Standard Model (SM) is probed at the quantum-loop level
- the consistency of SM is checked by comparing direct measurements with indirect determinations of input parameters, e.g. $m_t$ and $M_W$.
- the parameters of models beyond the SM can be constrained.

Global SM fit to all electroweak data: from LEPEWWG (Winter 2004)
• Most precise measurement of W boson mass was done at Tevatron.

• Most precise measurement of Top quark mass was done at Tevatron.
Phase II: Precision Measurements

**Z boson**

**top quark**

**Z → hadrons**

![Graph showing Z → hadrons](image)

**ALEPH**

**DELPHI**

**L3**

**OPAL**

**LEP experiments, CERN**

**Best Tevatron Run II (preliminary, March 2007)**

- **All-Jets: CDF (943 pb⁻¹)**
  - 171.1 ± 4.3

- **Dilepton: CDF (1030 pb⁻¹)**
  - 164.5 ± 5.6

- **Dilepton: D0 (1000 pb⁻¹)**
  - 172.5 ± 8.0

- **Lepton+Jets: CDF (940 pb⁻¹)**
  - 170.9 ± 2.5

- **Lepton+Jets: D0 (900 pb⁻¹)**
  - 170.5 ± 2.7

- **Tevatron (Run I/Run II, March 2007)**
  - 170.9 ± 1.8

**χ²/dof = 9.2/10**

**Tevatron experiments, Fermilab**
$\Delta M_t/M_t$ and $\Delta M_W/M_W$ Uncertainties Steadily Decreasing

$\Delta M_t/170.9 - 1 = 1.2$ GeV

$\Delta M_{top} = 1.2$ GeV

$\Delta M_W/80.398 - 1 = 0.025$ GeV

$\Delta M_W = 0.025$ GeV
Era of Precision Measurements @ Hadron colliders
Outlines

- Precision measurements at Tevatron Run-2 and LHC:
  - W/Z Physics

- Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:
  - W/Z, Top and Higgs Physics
$W$-boson physics

1. W-boson production and decay at hadron collider
2. How to measure W-boson mass and width?
3. High order radiative corrections:
   - QCD (NLO, NNLO, Resummation)
   - EW (QED-like, NLO)
4. ResBos-A and its predictions
W-boson production at hadron colliders

PDFs are known from deep inelastic scattering

\[ \sigma_{hh'\to W+X} = \sum_{f,f'} \int_0^1 dx_1 dx_2 \left\{ \phi_{f/h}(x_1) \hat{\sigma}_{ff'} \phi_{f'/h'}(x_2) + (x_1 \leftrightarrow x_2) \right\} \]

partonic “Born” cross section of $f \bar{f}' \to W^+$
PDFs: probability of finding a “parton” inside the hadron

ISR and FSR: (colored) initial and final states can radiate gluons
W-boson Decay

- **Hadronic mode**

  \[ W^+ \rightarrow q \bar{q} \]

  \[ Br \sim \frac{6}{9} \]

  hard to detect,
due to huge QCD backgrounds

- **Leptonic mode**

  \[ W^+ \rightarrow \ell^+ \nu_\ell \]

  \[ Br \sim \frac{3}{9} \]

  easy to identify,
but lack of \( p_z^\nu \)

unknown \( p_z^\nu \) → cannot reconstruct invariant mass of W boson
In (ud) c.m. system,

\[ \hat{p}_T^2 = \frac{1}{4} \hat{s} \sin^2 \theta \]

Jacobian factor

\[
\frac{d \cos \theta}{d \hat{p}_T^2} = -\frac{2}{\hat{s}} \frac{1}{\sqrt{1 - 4 \hat{p}_T^2/\hat{s}}} 
\]

\[
\Longrightarrow \frac{d\hat{\sigma}}{d\hat{p}_T^2} \sim \frac{d\hat{\sigma}}{d \cos \theta} \times \frac{1}{\sqrt{1 - 4 \hat{p}_T^2/\hat{s}}}
\]

\[ \Gamma_W \& q_T^W \]

Jacobin peak

sensitive region for measuring

\[ M_W : \hat{p}_T^e \sim 30 - 45 \text{ GeV} \]

\[ \Gamma_W : \text{not a good observable} \]
**Definition:**

\[ m_T^2(\ell, \nu) = 2 p_T^\ell p_T^\nu (1 - \cos \phi_{\ell\nu}) \]

from overall \( p_T \) imbalance

\[ \frac{d\sigma}{dm_T^2} \sim \frac{1}{\sqrt{1 - m_T^2/s}} \]

- unaffected by longitudinal boosts of \( \ell\nu \) system
- not sensitive to \( q_T^W \)
- tail knows about \( \Gamma_W \) (direct measurement)

\[ M_W : M_T \sim 60 - 100 \text{GeV} \]

\[ \Gamma_W : M_T > 100 \text{ GeV} \]
Theory requirements for Tevatron Run-II and LHC:

- Theory framework for Tevatron Run-I
  - $O(\alpha_S)$ (NLO-QCD) corrections
  - $O(\alpha)$ (QED) corrections
  
  } Adequate for comparison to Run-I data

- Run-II experimental targets:
  \[
  \frac{\delta \sigma_{tot}}{\sigma_{tot}} \sim 2 \ - \ 3\% \\
  \delta M_W \sim 30 \text{ MeV}
  \]

- Many factors contribute at a percent level:
  - $O(\alpha_S^2)$ (NNLO-QCD) corrections
  - $O(\alpha)$ (NLO-EW) corrections
  - uncertainties of parton distributions
  - power corrections to resummed cross sections

  } Task: consistent and efficient implementation of these effects
NNLO QCD corrections to the cross section

- NNLO hard cross section

- NNLO $K$-factor: 1.04 at Tevatron, 0.98 at LHC

- Scale dependence of order 1%

(CTEQ logo)
Rapidity distributions

- Little shape difference from NLO to NNLO
  - K-factor should be sufficient
- Z rapidity distributions could/will be used as input for pdf fits
Shortcoming in fixed order pQCD calculations

- Cannot describe data with small $q_T$ of W-boson.
- Cannot precisely determine $m_W$ at hadron colliders without knowing the transverse momentum of W-boson. Most events fall in the small $q_T$ region.

$\delta(q_T^2)$

Transverse momentum

(at NLO)
To describe data \( \rightarrow \) Resummation is needed

- Dashed: CSS (1,1,1)
- Solid: CSS (2,2,1)
- Perturbative

\[
\frac{d\sigma}{dQ_T} \quad (\text{pb}/\text{GeV})
\]

- Dotted: Pert (\( \alpha_s \))
- Dot-dashed: Pert (\( \alpha_s^2 \))

\( W^+ \)

\( Q_T (\text{GeV}) \)
Resummation effects agree with data very well

\[ P\bar{P} \rightarrow Z \] @ Tevatron
What is QCD resummation?

- All order quantum corrections

\[
\frac{d\hat{\sigma}}{dq_T^2} \sim \frac{1}{q_T^2} \sum_{n=1}^{\infty} \sum_{m=0}^{2n-1} \alpha_S^{(n)} \ln^{(m)} \left( \frac{Q^2}{q_T^2} \right) \\
\sim \frac{1}{q_T^2} \left\{ \alpha_S \left( L + 1 \right) \\
+ \alpha_S^2 \left( L^3 + L^2 + L + 1 \right) \\
+ \alpha_S^3 \left( L^5 + L^4 + L^3 + L^2 + L + 1 \right) \\
+ \cdots \right\}
\]

Resummation is to reorganize the results in terms of the large Log’s.
What is QCD resummation?

- reorganization of logs

\[
\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2} \left[ \alpha_s^2 \left( L + 1 \right) + \alpha_s^3 \left( L^3 + L^2 \right) + \cdots \right]
\]

Renormalization Group Technique

Diagram:
- Collinear + soft gluon
- Soft gluon
- Hard part
CSS resummation formalism

\[
\frac{d\sigma}{dq_T^2 dy dQ^2} = \frac{\pi}{S} \sigma_0 \delta \left( Q^2 - M_W^2 \right) \cdot [\text{Non-perturbative functions}]
\]

\[W = e^{-S(b)} \cdot C \otimes f(x_A) \cdot C \otimes f(x_B)\]

[Sudakov form factor \( S(b) = \int_{(\frac{Q}{\bar{\mu}})^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[ \ln \left( \frac{Q^2}{\bar{\mu}^2} \right) A(\bar{\mu}) + B(\bar{\mu}) \right] \) are functions of \((b, Q, x_A, x_B)\) which include QCD effects beyond Leading Twist.]

Collins-Soper-Sterman
Resummation effects agree with data very well

\[ \bar{P} \bar{P} \rightarrow Z \quad @ \text{Tevatron} \]

Predicted by ResBos:

A fortran program that includes the effect of multiple soft gluon emission on the production of W and Z bosons in hadron collisions.
W Charge Asymmetry: A Monitor of DFs

- Difference between $u(x)$ and $d(x)$ in proton cause $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$ to be boosted in opposite directions.

\[
A(y_w) = \frac{d \sigma (W^+)/dy_w - d \sigma (W^-)/dy_w}{d \sigma (W^+)/dy_w + d \sigma (W^-)/dy_w}
\]

\[
A(y_w) \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}
\]

- Rapidity charge asymmetry is sensitive to $d(x)/u(x)$ ratio at high-$x$ → primary interest of PDF fitters.

\[
A(\eta_l) = \frac{d \sigma (l^+)/d \eta_l - d \sigma (l^-)/d \eta_l}{d \sigma (l^+)/d \eta_l + d \sigma (l^-)/d \eta_l}
\]

- cannot reconstruct $y_w$ directly
- measure charged lepton only

\[A(\eta_l) = \frac{e^+}{e^+} \times \frac{u(p)}{\bar{d}(\bar{p})} W^-\]
Rapidity Distribution


$Q^2 = 5 \text{ GeV}^2$

$W^-$ and $W^+$ distributions

$W^+$ boosted in $p$ direction
$W^-$ boosted in $\bar{p}$ direction

u higher momentum

$u : \text{d} = 2 : 1$
All recent CTEQ and MSTW PDF fits include the effects of soft gluon resummation predicted by ResBos.
The complete NLO EW correction to W and Z boson production in hadron collisions are known.

The NLO QED corrections to the decay of W and Z bosons can be factored out from the complete NLO EW corrections in a gauge invariant way.
NLO EW corrections to W boson production

- Born
- Pure weak contribution
- W-Z box contribution
- Virtual photon contribution
- Real photon contribution
EW corrections (QED-like)

- Solid: QED-like
- Dotted: Full NLO EW corrections

Large shift in W mass $O(100 \text{ MeV})$
Precision measurements require accurate theoretical predictions.

- **ResBos-A**: improved ResBos by including final state NLO QED corrections to $W$ and $Z$ production and decay.

<table>
<thead>
<tr>
<th>Resum+Born</th>
<th>Resum+NLO</th>
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<td><img src="image1.png" alt="Diagram" /> + <img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /> + <img src="image4.png" alt="Diagram" /> + <img src="image5.png" alt="Diagram" /></td>
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</table>

• and denote FQED radiation corrections, which dominates the W mass shift.

Qing-Hong Cao and CPY

hep-ph/0401026
W Mass @ CDF Run-2

W→ev transverse mass distribution

CDF II preliminary \[ \int L \, dt \approx 2.4 \, fb^{-1} \]

{\begin{itemize}
  \item data
  \item MC
  \item background
\end{itemize}

\[ \Delta m_W^{\text{stat}} = 15 \, \text{MeV/c}^2 \]

\[ \chi^2/\text{dof} = 70 / 48 \]

Statistical error only.
$p_T^e$ is sensitive to $q_T^W$.

Cuts:
- $p_T^{e^+} > 25$ GeV
- $E_T > 25$ GeV
- $|\eta^{e^+}| < 1.2$
W Boson $q_T @ D0$ Run-2

Figure: Phys. Rev. Lett. 100, 102002 (2008)
Z-boson physics

1. Help to improve the measurement of W-boson
   - calibrate detector
   - indirect measurement of W-boson width

2. ResBos-A and its predictions
   - effective Born approximation
   - various kinematical distributions
Precision measurement of Z-boson

- help to calibrate detector

Mass information comes primarily from lepton $p_T$
- Run 2 goal: calibrate $p_T$ to $\sim 0.01\%$

Use Z decays to model boson $p_T$ distribution, detector response to hadronic recoil energy
Combine lepton and neutrino $p_T$ to form transverse mass ($m_T$) for best statistical power
Including photon and Z boson interference effect

Photon and Z interference effect has been implemented, therefore ResBos-A can be used to low energy Drell-Yan process.

Effective Born Approximation is adopted in order to include the dominant higher order EW corrections around the Z-pole.

\[ \alpha \rightarrow \alpha(\hat{s}) , \quad v_f \rightarrow v^\text{eff}_f = \frac{1}{2s_w} \frac{M_Z}{M_W} (I_3^f - 2Q_f \sin^2 \theta_{\text{eff}}^f) \]

Effect from pQCD soft gluon resummation is included, at the same level of accuracy as that for W boson production and decay.
Z Mass @ CDF Run-2

Z→μ+μ- invariant mass distribution

CDF II preliminary \( \int L \, dt \approx 2.3 \text{ fb}^{-1} \)

\[ \Delta m_z^{\text{stat}} = 12 \text{ MeV}/c^2 \]

\[ \chi^2/\text{dof} = 27/29 \]

- data
- MC

Events / 0.5 GeV/c^2

Statistical error only.
First part of Conclusion and outlook

1. We are entering the era of precision measurement at hadron colliders.

2. For precision measurement of $W$ mass, it is needed to include both QCD and EW corrections consistently and efficiently.
   As the first step toward this goal, ResBos-A includes both the initial state multiple soft gluon resummation effect and final state QED corrections (which dominates the W mass shift).

3. Precision measurement of $Z$ boson, via the ratio method, can improve $W$-boson mass measurement and provide indirect measurement of $W$-boson width.

Precision Electroweak Physics at Hadron Colliders
http://hep.pa.msu.edu/resum/
Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:

W/Z, Top and Higgs Physics
New Physics signal found?

Excitement at 10 years ago

CDF Run 1A Data (1992-93)

High-x gluon not well known


…can be accommodated in the Standard Model
Cross sections at the LHC

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just "rescaled" scattering at the Tevatron.
- Small typical momentum fractions $x$ in many key searches:
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony
LHC Parton Kinematics

Sensitive to new region of $x$ and $Q$ values.

Need better determination of PDFs

Need new kind of global analysis, such as “The Combined PDF and $P_T$ Fits”
Impact of new CTEQ PDF sets to SM processes: $W$, $Z$, top, Higgs

CTEQ6.6 PDF’s, heavy flavors and PDF induced correlations between LHC observables

In collaboration with

Hong-Liang Lai, Pavel Nadolsky, Qing-Hong Cao, Joey Huston, Jon Pumplin, Dan Stump, Wu-Ki Tung
Global analysis at Michigan State/Taiwan/Washington

■ a part of the Coordinated Theoretical Experimental study of QCD (CTEQ) in U.S.A.

■ development of general-purpose PDF’s

(Wu-Ki Tung and collaborators)

■ new CTEQ6.6M standard set and 44 extreme eigenvector sets (arXiv:0802.0007)

► improved treatment of $s$, $c$, $b$ PDF’s
► correlation analysis of collider observables
► available in the LHAPDF-5.4 library and at www.cteq.org
“Standard candle” processes: $W$, $Z$, $t\bar{t}$ production

Cross sections for $pp \rightarrow W^\pm X$, $pp \rightarrow Z^0 X$ at the LHC can be measured with accuracy $\delta\sigma/\sigma \sim 1\%$ (tens of millions of events even at low luminosity)

These measurements will be employed to monitor the LHC luminosity in real time and tightly constrain PDF’s (Dittmar, Pauss, Zurcher; Khoze, Martin, Orava, Ryskin; Giele, Keller’;...)

We will see that $t\bar{t}$ production may also potentially become a calibration process at the LHC because of its strong anticorrelation with $Z$ production
CTEQ6.6 PDF’s

- CTEQ6.6 $u$, $d$ are above CTEQ6.1 at $x \lesssim 10^{-2}$
  - The result of suppressed charm contribution to $F_2(x, Q)$ at HERA in the GM-VFN scheme
- very different strange PDF’s

CTEQ6.1M (zero-mass scheme)
Impact of charm contributions to DIS at HERA

- $W,Z$ production at the LHC: $x \sim 10^{-3} - 10^{-2}$

- Suppression of charm contribution to $F_2(x, Q^2)$ in the GM-VFN scheme results in larger $\bar{u}(x), \bar{d}(x)$ at small $x \Rightarrow$ larger $\sigma_{W,Z}^{LHC}$

$$\frac{\delta \bar{q}_{\text{light}}(x)}{\bar{q}_{\text{light}}(x)} = 3\% \Rightarrow \delta L_{qi\bar{a}_j} / L_{qi\bar{a}_j} = 2(\delta \bar{q}_{\text{light}} / \bar{q}_{\text{light}}) = 6\%$$
At large $x$, the extremes are given by eigenvector sets 23,24 and 31,32.
Such changes in $\sigma_{Z,W}$ exceed NNLO corrections or anticipated experimental error of $\sim 1\%$

Two latest MSTW predictions are compatible with the CTEQ6.6 result
At the LHC, $\sigma_{W,Z}(\text{CTEQ6.6M}) \approx 1.06 \sigma_{W,Z}(\text{CTEQ6.1M})$

- reflects a 6% increase in light quark luminosities

$$L_{q_i \bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q)\bar{q}_j(x_2, Q)$$ at relevant $x$ and $Q$
Tevatron and LHC cross sections

\[ \sigma_{\pm} \pm \delta \sigma_{PDF} \text{ in units of } \sigma_{(CTEQ66M)} \]

Tevatron Run 2, NLO

- CTEQ6.6
- CTEQ6.1

\[ \sigma_{\pm} \pm \delta \sigma_{PDF} \text{ in units of } \sigma_{(CTEQ66M)} \]

LHC, NLO

- CTEQ6.6
- CTEQ6.1

- NLO calculations using ResBos, WTTOT, MCFM
- CTEQ6.5 and CTEQ6.6 cross sections are qualitatively same
- At LHC, \( \sigma_{W,Z}(CTEQ6.6M) \approx 1.06 \sigma_{W,Z}(CTEQ6.1M) \)
  - reflects a 6% increase in light quark luminosities
  \[ L_{q_i \bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q) \bar{q}_j(x_2, Q) \] at relevant \( x \) and \( Q \)
- finer differences with CTEQ6.5 in precision predictions for \( W \), \( Z \) production, strange-quark scattering

C.-P. Yuan (MSU)
Correlations and ratio of $W$ and $Z$ cross sections

Radiative contributions, PDF dependence have similar structure in $W$, $Z$, and alike cross sections; cancel well in Xsection ratios.
Correlations between physical observables through PDF degrees of freedom

Misleadingly simple questions

1. Why are PDF induced variations in $\sigma_W$ and $\sigma_Z$ strongly correlated?

2. Since both $W$ and $Z$ are mostly produced in light-quark scattering, is their PDF uncertainty mostly coming from light-quark PDF’s?

3. How can we test this?

Answers can be found by systematically studying correlations in the PDF parameter space
An inefficient application of the Hessian method

Compute $\sigma_W$ for 44 extreme PDF eigensets

Find eigenparameter(s) producing largest variation(s), such as #4 or 8

Check that the same eigenparameters produce largest variations in $\sigma_Z$

It is not obvious how to relate abstract eigenparameters to physical PDF’s $u(x)$, $d(x)$, etc.
Correlation analysis for collider observables

(J. Pumplin et al., PRD 65, 014013 (2002); P.N. and Z. Sullivan, hep-ph/0110378)

A technique based on the Hessian method

For $2N$ PDF eigensets and two cross sections $X$ and $Y$:

$$\Delta X = \frac{1}{2} \sqrt{\sum_{i=1}^{N} \left( X_i^{(+) - X_i^{(-)} \right)^2}$$

$$\cos \varphi = \frac{1}{4\Delta X \Delta Y} \sum_{i=1}^{N} \left( X_i^{(+)} - X_i^{(-)} \right) \left( Y_i^{(+)} - Y_i^{(-)} \right)$$

$X_i^{(\pm)}$ are maximal (minimal) values of $X_i$ tolerated along the $i$-th PDF eigenvector direction; $N = 22$ for the CTEQ6.6 set
Correlation angle $\varphi$

Determines the parametric form of the $X - Y$ correlation ellipse

$$X = X_0 + \Delta X \cos \theta$$
$$Y = Y_0 + \Delta Y \cos(\theta + \varphi)$$

$X_0, Y_0$: best-fit values
$\Delta X, \Delta Y$: PDF errors

$\cos \varphi \approx \pm 1$: Measurement of $X$ imposes tight constraints on $Y$
$\cos \varphi \approx 0$: loose constraints on $Y$
Correlations and ratios of $W$ and $Z$ cross sections at the LHC

$W^\pm$ & $Z$ cross sections at the LHC

Somewhat surprisingly, the remaining PDF uncertainty is mostly due to $s(x)$
Correlations of $Z$ and $t\bar{t}$ cross sections with PDF’s

LHC $Z$, $W$ cross sections are strongly correlated with $g(x)$, $c(x)$, $b(x)$ at $x \sim 0.005$

∴ they are strongly anticorrelated with processes sensitive to $g(x)$ at $x \sim 0.1$ ($t\bar{t}$, $gg \to H$ for $M_H > 300$ GeV) as a consequence of momentum sum rule
Measurements of $\sigma_{t\bar{t}}$ and $\sigma_Z$ probe the same (gluon) PDF degrees of freedom at different $x$ values
Correlations between $\sigma(gg \rightarrow H^0)$, $\sigma_Z$, $\sigma_{t\bar{t}}$

As $M_H$ increases:

- $\cos \varphi(\sigma_H, \sigma_Z)$ decreases
- $\cos \varphi(\sigma_H, \sigma_{t\bar{t}})$ increases
$t\bar{t}$ production as a standard candle process

- Measurements of $\sigma_{t\bar{t}}$ with accuracy $\sim 5\%$ may be within reach
- Would provide additional constraints on the large-$x$ gluon PDF
- Will be useful for monitoring of $L_{LHC}$ luminosity in the first years and normalization of LHC event rates

See also the talk by M. Csakon; Moch, Uwer, arXiv:0804.1476; Cacciari et al., arXiv:0804.2800; Kidonakis, Vogt, arXiv:0805.3844
Top Quark Pair production rates

At Tevatron Run-2, uncertainty induced by PDFs is sizable.

Uncertainty induced by factorization (and renormalization) scale dependence is large at the LHC. Hence, NNLO calculation is needed.
Use top quark pair production rate to determine the mass of top quark
What’s top mass?

What’s the top mass in a full event generator, such as PYTHIA?

NOBODY KNOWS

Parton showers generate some higher order corrections in the event shape, but with approximations.
Conclusions

- CTEQ6.6 study confirms most findings of the CTEQ6.5 analyses; predicts some differences in cross sections for heavy-flavor scattering, LHC EW precision physics

- Free parameters in CTEQ6.6 strange PDFs probe a new direction in the PDF parameter space, affect predictions for strange-quark scattering, $\sigma_Z/\sigma_W$ at the LHC

- Analysis of correlations in PDF parameter space is a powerful technique to understand relations between physics observables through shared PDF degrees of freedom

- At the LHC, CTEQ6.6 $t\bar{t}$ cross section is anticorrelated with $Z$ cross section via the gluon PDF; can potentially be used as an additional observable to monitor the LHC luminosity
Substantial contributions to Higgs cross section from LO to NLO and from NLO to NNLO.

For this reason, Higgs cross sections most often calculated to NNLO (with NNLO pdf’s).
Higgs cross section at NNLO is 30% (115 GeV) to 9% (300 GeV) larger at the LHC now than in 2003

Tevatron cross section is +9% (115 GeV) to -9% (200 GeV)

About half or more of the effect is from the changes in the gluon distribution in MRST->MSTW

- for low $x < 0.05$, MSTW2008 gluon $>$ MRST2002 gluon
- for moderate $x$, $0.05 < x < 0.5$, MRST2002 gluon $>$ MSTW2008 gluon

(Most of ) rest of change is from increase in $\alpha_s$ at NNLO

- $0.1154$-$0.1171$
- note that $\alpha_s$ is included in the global fit; CTEQ fixes it at world average

EW corrections also cause some change
Change in gluon

- About half of the change happened in 2006 and half in 2008
- Due (at least partially) to changes in the heavy quark scheme
  - more light quarks needed at small $x$
  - flavor threshold effects more complicated in MSTW approach than in CTEQ due to counting of orders (see arXiv:0809.0714)

- Change may have worked for Barack Obama but it upsets experimentalists
There’s been some change in the CTEQ gluon distribution as well due to the switch to the heavy quark mass scheme, but not as much.

And since we use the world average of $\alpha_s$ (and that hasn’t changed much), the Higgs cross section predictions have been somewhat more stable.
Comparisons at NLO

CTEQ and MSTW fairly close in x range for Higgs production at LHC
Compare gluons
CTEQ6.6 and MSTW2008NLO predictions for W and Z cross sections agree amazingly well.

Compare to situation with MRST2004 and CTEQ6.6.
Outlines

Precision measurements at Tevatron Run-2 and LHC:

W/Z Physics

Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:

W/Z, Top and Higgs Physics
Backup Slides
## W Boson Mass Uncertainties (MeV)

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<th>$M_T$</th>
<th>Electron $p_T$</th>
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<td>$W$ statistics</td>
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</tr>
<tr>
<td>$W$ boson $p_T$</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>QED</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>$W$ boson width</td>
<td>&lt;5</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Total</td>
<td>45</td>
<td>48</td>
</tr>
</tbody>
</table>

Important for a measurement with 25 MeV uncertainty (4 fb$^{-1}$)
PDF’s \( f_a(x,Q) \) are parametrized with a flexible form motivated by physics considerations (Regge behavior, spectator counting, for example) at fixed small \( Q_0 \) (1.3 GeV for CTEQ) and then evolved for \( Q>Q_0 \) by DGLAP

- assume for most of the general analyses that the \( c \) and \( b \) distributions are zero at scales below their masses and are generated by QCD evolution above

- Parametrization of parton distributions at \( Q_0 \) used to obtain the CTEQ5 and CTEQ6 parton distributions contained 5 shape parameters (apart from normalization) for each flavor

- global analysis data sets not sufficiently constraining to determine all of the parameters, so a number are frozen at some particular (motivated) values

- 20 free parameters for CTEQ6.1/6.5 and 22 for CTEQ6.6 (see next slide)

- For CTEQ6.5/6.6, adopt a simpler form with 4 shape parameters for the valence quarks \( u_v(x) \), \( d_v(x) \) and the gluon \( g(x) \)

\[
f(x) = a_o x^{a_1} (1 - x)^{a_2} e^{a_3 x + a_4 x^2}
\]

- a reasonable generalization of the conventional minimal form

\[
f(x) = a_o x^{a_1} (1 - x)^{a_2}
\]

- which combines Regge behavior at \( x \to 0 \) and spectator counting at \( x \to 1 \)

- Both forms above are positive definite and have simplified logarithmic derivatives
CTEQ PDF Parametrization

- Is this form flexible enough?
- Remember the lesson of Tevatron Run-1 jets, where low x and high x PDFs can easily be (artificially) tied together through the parametrization.
- We find that significantly better fits cannot be achieved by introducing additional parameters or changing the functional form
  - NB: prior to CTEQ6.6, the analysis generally assumed
    \[ s(x) = \bar{s}(x) \propto \bar{d}(x) + \bar{u}(x) \]
  - that ansatz has been dropped in CTEQ6.6