

CTEQ6.6 PDF's, heavy flavors, correlations between LHC observables

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in collaboration with

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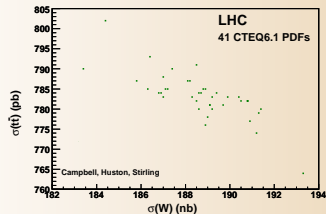
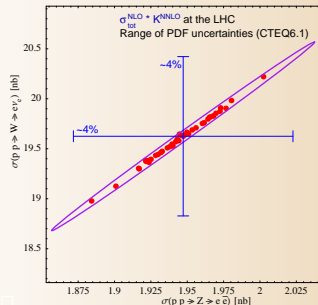
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CTEQ6.6 analysis is near completion

Why so soon?

- additions to, and improvements over the CTEQ6.5 analysis
- some changes in predictions for heavy-flavor scattering, LHC cross sections
- exploration of PDF-induced correlations between LHC observables
⇒ important for the monitoring of parton and collider luminosities, determination of new physics parameters

Noteworthy (anti)correlations



CTEQ6.5 global analysis (Jon, Liang, Wu-Ki, and collaborators)

PDF's of the CTEQ6.5 family released in late 2006; major advances compared to the CTEQ6.1 set

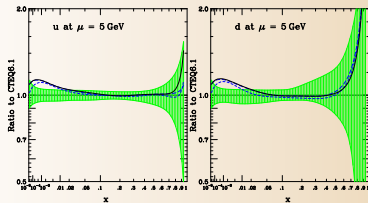
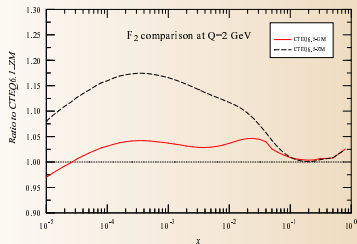
- full implementation of general-mass "simplified ACOT- χ " scheme

(Tung et al., hep-ph/0611254; Aivasis et al.; Collins, 1998; Kramer, Olness, Soper; Tung, Kretzer, Schmidt; ...)

- ▲ consequences for observables sensitive to c and b quark scattering, especially $F_2^{c,b}(x, Q^2)$

- ▲ changes in light-quark (u, d) PDF's caused by reduced charm contributions to DIS neutral-current data

- ▲ differences from zero-mass (CTEQ6.1) predictions at the LHC



CTEQ6.5 global analysis (Jon, Liang, Wu-Ki, and collaborators)

■ a detailed investigation of strangeness degrees of freedom probed by NuTeV and CCFR data (H.-L. Lai et al., hep-ph/0702268)

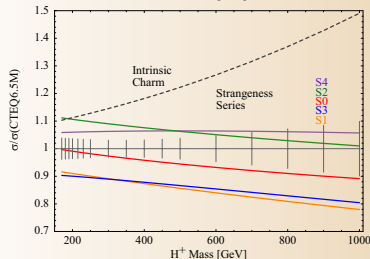
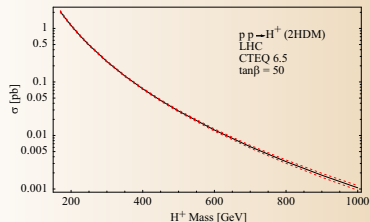
▲ the ansatz $s(x) \propto \bar{u}(x) + \bar{d}(x)$ for (anti)strangeness PDF's is discarded in favor of independent parametrizations for $s(x)$, $\bar{s}(x)$

▲ possibility of $\bar{s}(x) \neq s(x)$ explored

▲ $s(x) = \bar{s}(x)$ is compatible with the existing data

▲ NLO predictions for processes sensitive to $s(x)$ ($pp^{(-)} \rightarrow W^+ cX$, $pp^{(-)} \rightarrow H^+_{MSSM} X$)

■ A study of "intrinsic charm" scenarios (J. Pumplin et al., hep-ph/0701220)



Developments since CTEQ6.5 \Rightarrow CTEQ6.6

- NNLO evolution and DIS Wilson coefficients in the SACOT- χ scheme is for the most part implemented *(Liang)*
 - ▶ public fits still done at NLO
 - ▶ small differences between the old and new codes
- Independent strange PDF's are included in the general-purpose PDF set

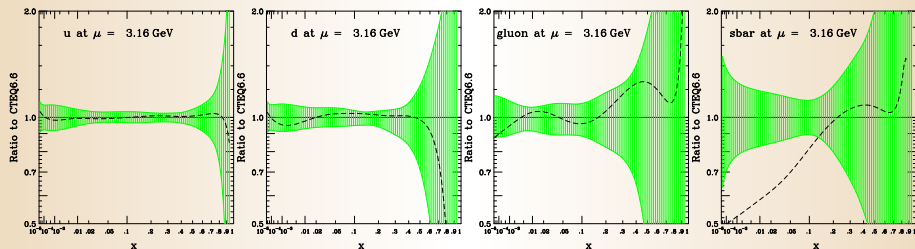
$$s(x) = \bar{s}(x) = A_0 x^{A_1} (1-x)^{A_2} \text{ at } Q_0 = 1.3 \text{ GeV}$$

A_0, A_2 free; A_1 the same as for \bar{u} and \bar{d}

- 22 free PDF parameters (vs. 20 in CTEQ6.1 and 6.5)
- extended x range ($10^{-7} \leq x \leq 1$)

CTEQ6.6 PDF's

Dashes: CTEQ6.1M



- CTEQ6.1 u, d are below CTEQ6.6 by 2-3% at $x \sim 10^{-3}$; below CTEQ6.5 by up to 4%
- very different strange PDF's

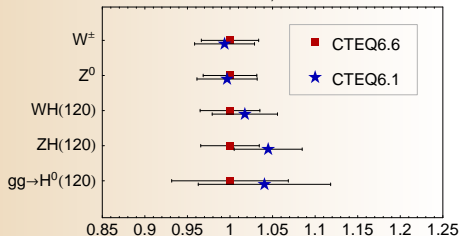
Improved agreement with $F_2^{c,b}(x, Q^2)$ and $\sigma^{c,b}(x, Q^2)$ data

using the updated CTEQ NLO code

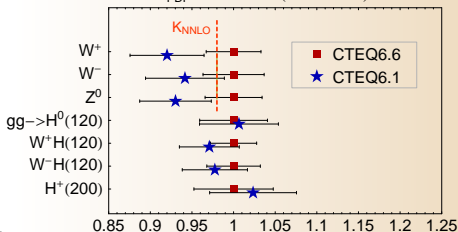
Experiment	Npt	$\chi^2(\text{CTEQ6.5M})$	$\chi^2(\text{CTEQ6.6M})$	$\Delta\chi^2$
HN+67F2c	8	13.5	7.5	-6
HN+90X0c	10	16.4	14.1	-2.3
ZN+67F2c	18	26	14.2	-11.8
ZN+80F2c	27	35.1	17.8	-17.3
HN+90X0b	10	15.4	6.2	-9.2

Tevatron and LHC cross sections

$\sigma \pm \delta\sigma_{\text{PDF}}$ in units of $\sigma(\text{CTEQ66M})$
Tevatron Run-2, NLO



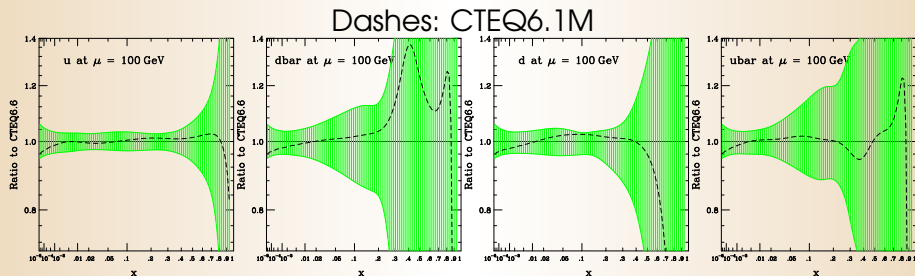
$\sigma \pm \delta\sigma_{\text{PDF}}$ in units of $\sigma(\text{CTEQ66M})$ at LHC



- NLO calculations using ResBos, WTTOT, MCFM
- CTEQ6.5 and CTEQ6.6 cross sections are qualitatively same
- At LHC, $\sigma_{W,Z}(\text{CTEQ6.6M}) \approx 1.06\sigma_{W,Z}(\text{CTEQ6.1M})$
 - ▶ reflects a 6% increase in light quark luminosities

$$\mathcal{L}_{q_i \bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q) \bar{q}_j(x_2, Q)$$
 at relevant x and Q
- finer differences with CTEQ6.5 in precision predictions for W , Z production, strange-quark scattering

Impact of charm contributions to DIS at HERA

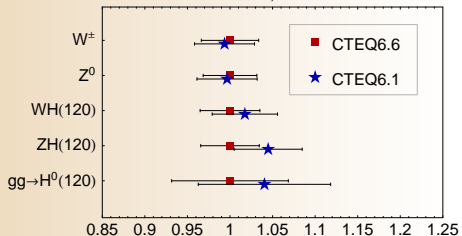


- W, Z production at the LHC: $x \sim 10^{-3} - 10^{-2}$
- Suppression of charm contribution to $F_2(x, Q^2)$ in the GM-VFN scheme results in larger $\bar{u}^j(x)$, $\bar{d}^j(x)$ at small $x \Rightarrow$ larger $\sigma_{W,Z}^{LHC}$

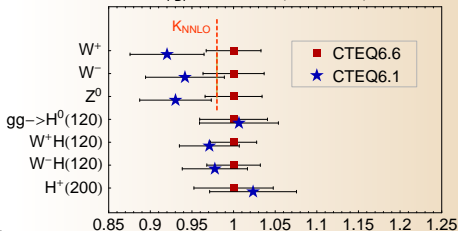
$$\delta \bar{q}_{light}(x) / \bar{q}_{light}(x) = 3\% \quad \Rightarrow \quad \delta \mathcal{L}_{q_i \bar{q}_j} / \mathcal{L}_{q_i \bar{q}_j} = 2(\delta \bar{q}_{light} / \bar{q}_{light}) = 6\%$$

Tevatron and LHC cross sections

$\sigma \pm \delta\sigma_{\text{PDF}}$ in units of $\sigma(\text{CTEQ66M})$
Tevatron Run-2, NLO



$\sigma \pm \delta\sigma_{\text{PDF}}$ in units of $\sigma(\text{CTEQ66M})$ at LHC



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 - $\mathcal{L}_{q_i \bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q) \bar{q}_j(x_2, Q)$ at relevant x and Q
- finer differences with CTEQ6.5 in precision predictions for W , Z production, strange-quark scattering

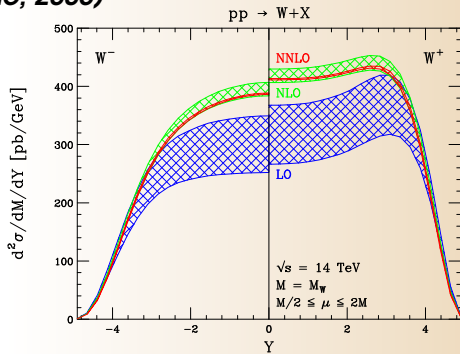
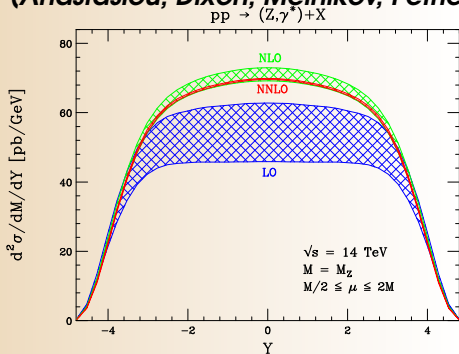
“Standard candle” processes: W , Z , $t\bar{t}$ production

- 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

W and Z rapidity distributions at NNLO

(Anastasiou, Dixon, Melnikov, Petriello, 2003)



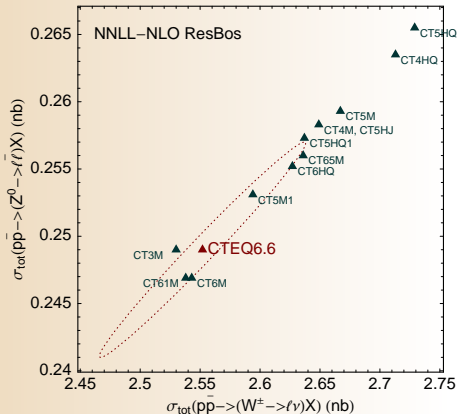
- Tiny scale dependence ($\sim 1\%$)
- For $|y| < 2$, NNLO leads to a uniform rescaling

$$\sigma_{NNLO} \approx K_{NNLO} \cdot \sigma_{NLO}; K_{NNLO}^{LHC} \approx 0.98$$

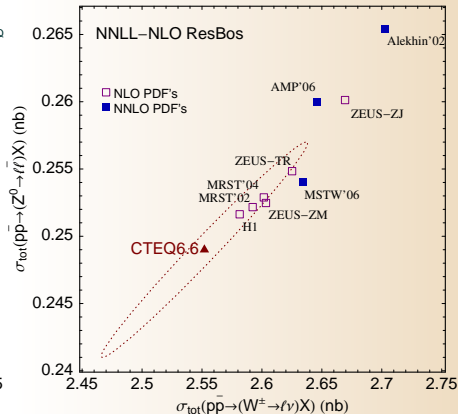
- Larger corrections at forward rapidities

W and Z cross sections at the Tevatron

W[±] & Z cross sections at the Tevatron Run-2

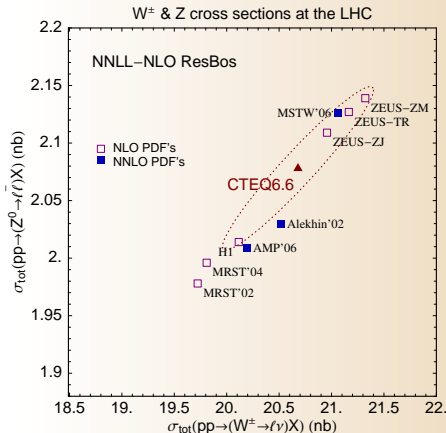
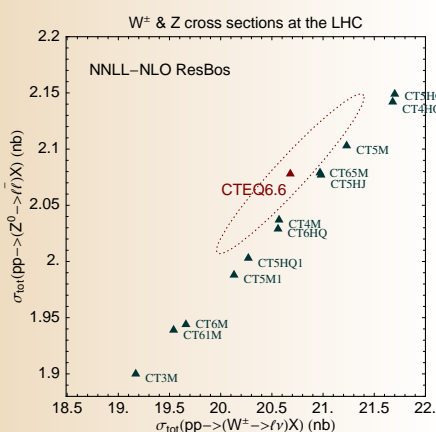


W[±] & Z cross sections at the Tevatron Run-2



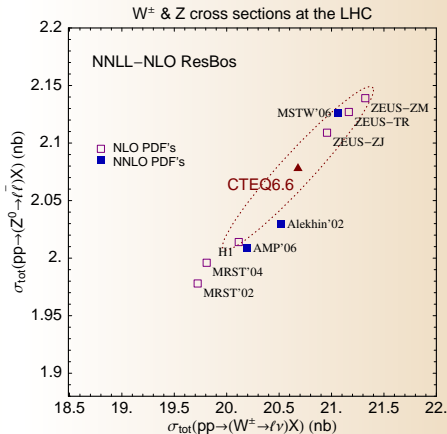
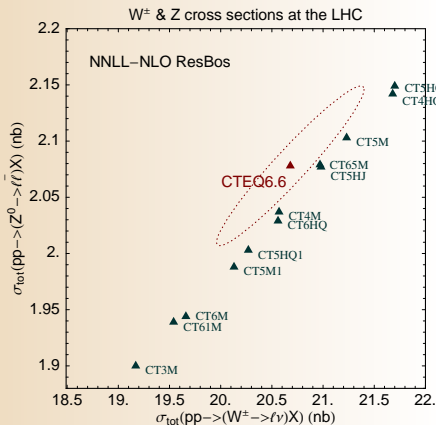
- The ellipse corresponds to $\Delta\chi^2_{\text{scaled}} = 100$ (not a 90% c.l. !)
- strong correlation between σ_W and σ_Z
- CTEQ6.6 more or less agrees with CTEQ6.1 and 6.5, MSTW'06

W and Z cross sections at the LHC



- CTEQ6.6 ellipse is shifted along its minor axis compared to all other CTEQ sets (differences in s , c , b sectors)
- MSTW'06 moved higher toward CTEQ6.5M compared to MRST'04

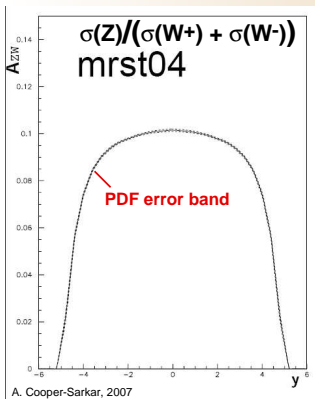
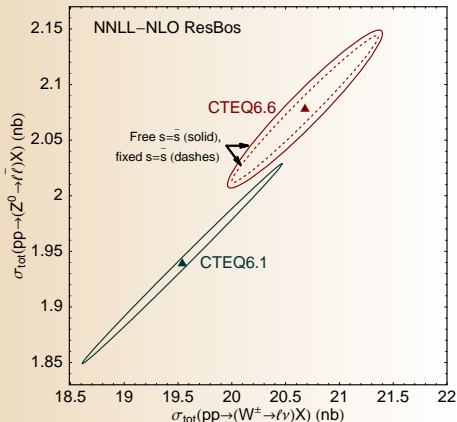
W and Z cross sections at the LHC



- the latest PDF's are in a better overall agreement than a year ago

Correlations and ratio of W and Z cross sections

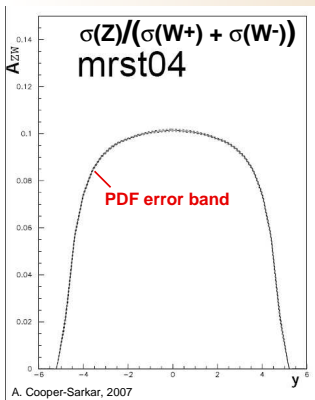
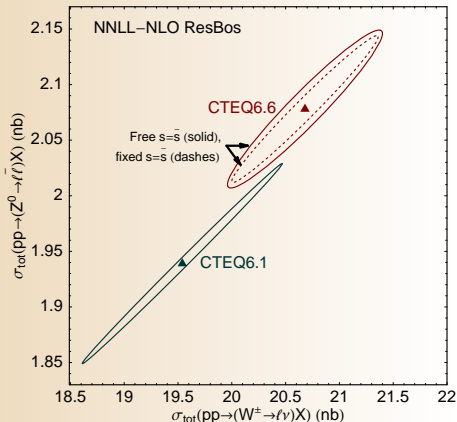
W^\pm & Z cross sections at the LHC



Radiative contributions, PDF dependence have similar structure in W , Z , and alike cross sections; cancel well in Xsection ratios

Correlations and ratio of W and Z cross sections

W^\pm & Z cross sections at the LHC



Somewhat surprisingly, the remaining PDF uncertainty is mostly due to $s(x)$

Correlations between physical observables through PDF degrees of freedom

Misleadingly simple questions

1. Why are variations in σ_W and σ_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

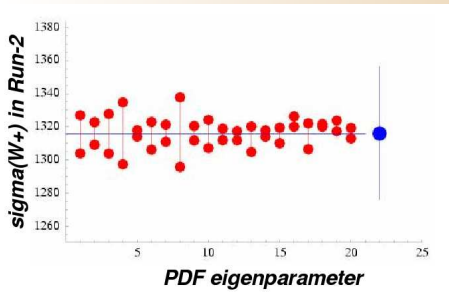
An inefficient application of the Hessian method

😊 Compute σ_W for 44 extreme PDF eigensets

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

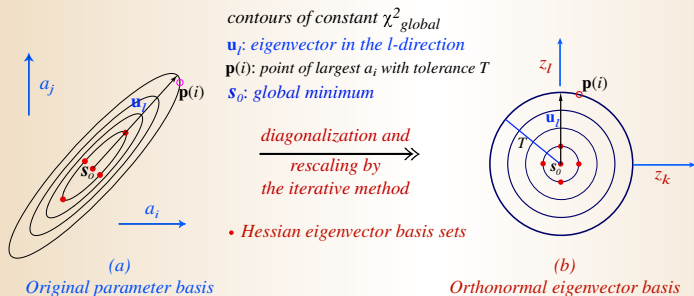
😊 Check that the same eigenparameters produce largest variations in σ_Z

😞 It is not obvious how to relate abstract eigenparameters to physical PDF's $u(x)$, $d(x)$, etc.



Tolerance hypersphere in the PDF space

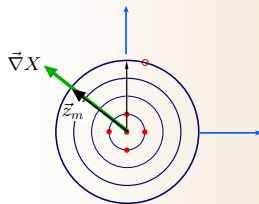
2-dim (i,j) rendition of N -dim (22) PDF parameter space



An ellipse $\chi^2 - \chi^2_{\text{min}} \leq T^2$ in space of N physical PDF parameters $\{a_i\}$ is mapped onto a hypersphere of radius T in space of N orthonormal PDF parameters $\{z_i\}$

Tolerance hypersphere in the PDF space

2-dim (i,j) rendition of N-dim (22) PDF parameter space



(b)

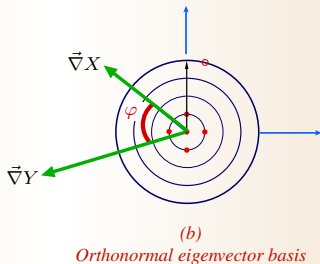
Orthonormal eigenvector basis

PDF error for a physical observable X is given by

$$\Delta X = \vec{\nabla}X \cdot \vec{z}_m = |\vec{\nabla}X| = \frac{1}{2} \sqrt{\sum_{i=1}^N (X_i^{(+)} - X_i^{(-)})^2}$$

Tolerance hypersphere in the PDF space

2-dim (i,j) rendition of N-dim (22) PDF parameter space



Correlation cosine for observables X and Y :

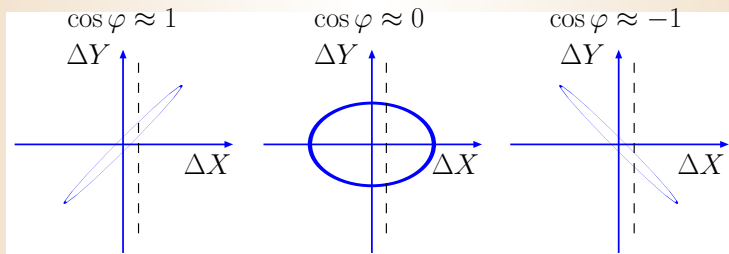
$$\cos \varphi = \frac{\vec{\nabla}X \cdot \vec{\nabla}Y}{\Delta X \Delta Y} = \frac{1}{4\Delta X \Delta Y} \sum_{i=1}^N \left(X_i^{(+)} - X_i^{(-)} \right) \left(Y_i^{(+)} - Y_i^{(-)} \right)$$

Role of the correlation angle

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

$$X = X_0 + \Delta X \cos \theta$$

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



$\cos \varphi \approx \pm 1$:
 $\cos \varphi \approx 0$:

Measurement of X imposes

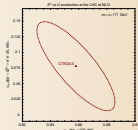
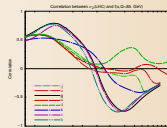
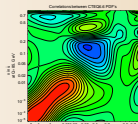
tight
loose

constraints on Y

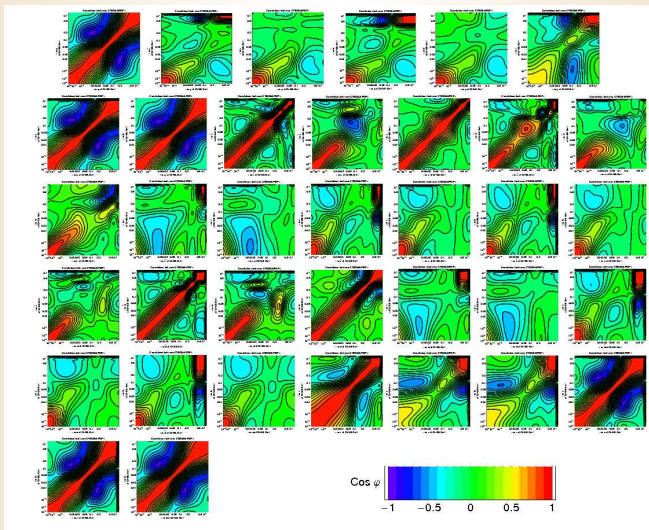
Types of correlations

X and Y can be

- two PDFs $f_1(x_1, Q_1)$ and $f_2(x_2, Q_2)$
(plotted as $\cos \varphi$ vs x_1 & x_2)
- a physical cross section σ and PDF $f(x, Q)$
(plotted as $\cos \varphi$ vs x)
- two cross sections σ_1 and σ_2

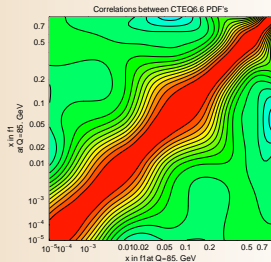


Correlations between $f_1(x_1, Q)$ and $f_2(x_2, Q)$ at $Q = 85 \text{ GeV}$

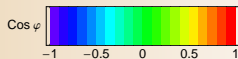
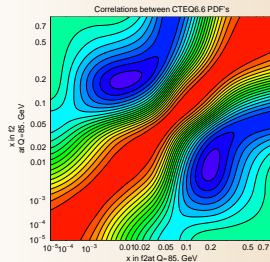


Correlations between $f(x_1, Q)$ and $f(x_2, Q)$ at $Q = 85 \text{ GeV}$

$f_1(x_1, Q)$ vs. $f_1(x_2, Q)$

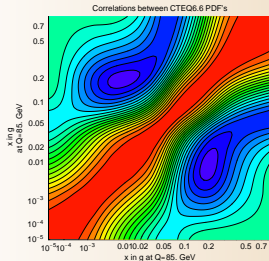
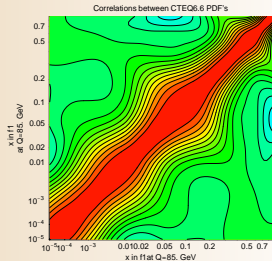


$f_2(x_1, Q)$ vs. $f_2(x_2, Q)$

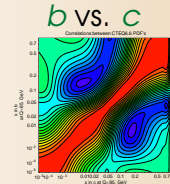
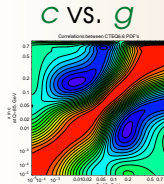
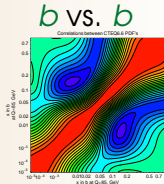
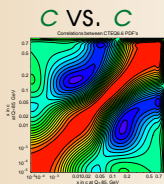


Can you guess which PDF's these are?

Correlations between $f(x_1, Q)$ and $f(x_2, Q)$ at $Q = 85 \text{ GeV}$ $u(x_1, Q)$ vs. $u(x_2, Q)$ vs. $g(x_1, Q)$ vs. $g(x_2, Q)$



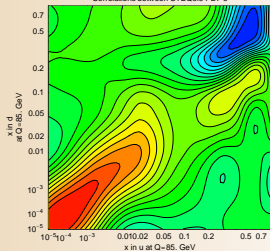
Correlation patterns look similar for g, c, b PDF's (no intrinsic charm here!)



Correlations between $f_1(x_1, Q)$ and $f_2(x_2, Q)$ at $Q = 85 \text{ GeV}$

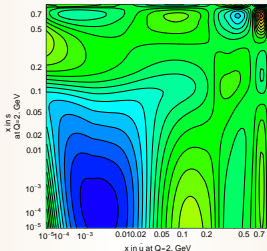
d vs u

Correlations between CTEQ6.6 PDF's



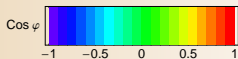
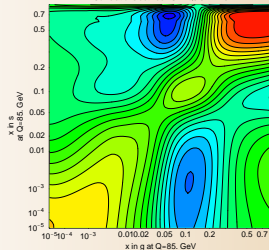
s vs \bar{u} at $Q=2$

Correlations between CTEQ6.6 PDF's



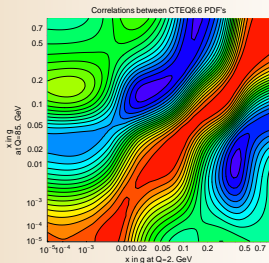
s vs. g

Correlations between CTEQ6.6 PDF's



Sometimes there is a clear physics reason behind the correlation (e.g., sum rules or assumed Regge-like behavior); sometimes not

Correlations between $g(x_1, 2 \text{ GeV})$ and $g(x_2, 85 \text{ GeV})$

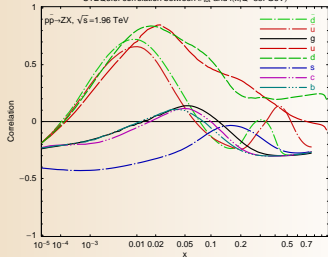


Gluons at $Q = 85 \text{ GeV}$ are correlated with gluons at $Q = 2 \text{ GeV}$ and larger x because of DGLAP evolution

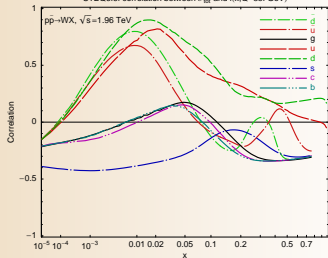
Correlations between W, Z cross sections and PDF's

Tevatron Run-2

CTEQ6.6: correlation between σ_{ZZ} and $f(x, Q=85, \text{GeV})$

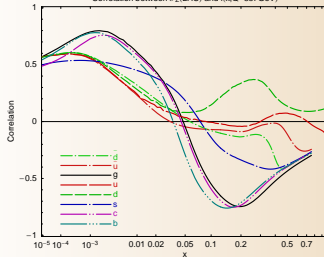


CTEQ6.6: correlation between σ_{WW} and $f(x, Q=85, \text{GeV})$

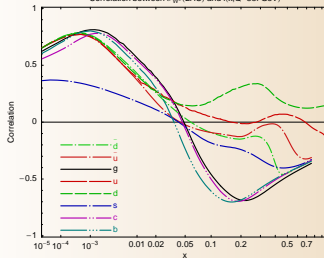


LHC

Correlation between $\sigma_{ZZ}(\text{LHC})$ and $f(x, Q=85, \text{GeV})$



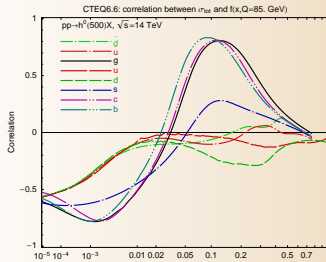
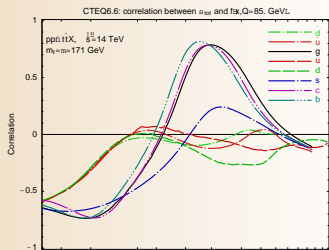
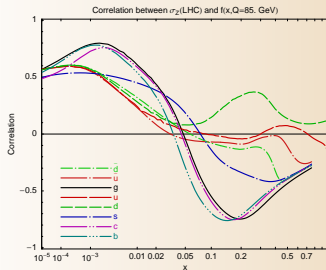
Correlation between $\sigma_{WW}(\text{LHC})$ and $f(x, Q=85, \text{GeV})$



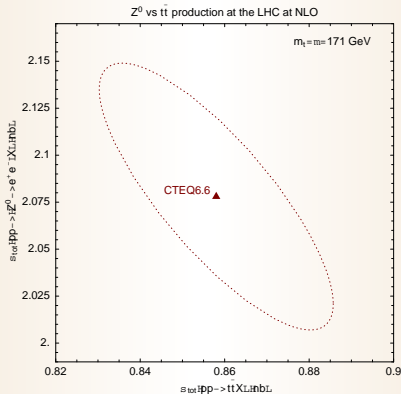
A surprising discovery

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

\therefore they are strongly anticorrelated with processes sensitive to $g(x)$ at $x \sim 0.1$ ($t\bar{t}$, $gg \rightarrow H$ for $M_H > 300$ GeV)



$t\bar{t}$ vs Z cross sections at the LHC

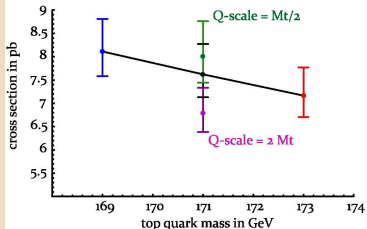


Measurements of $\sigma_{t\bar{t}}$ and σ_Z probe the same (gluon) PDF degrees of freedom!

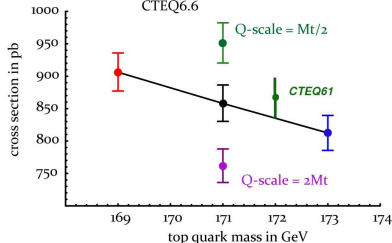
To efficiently utilize this feature, we need an NNLO calculation for $t\bar{t}$ to reduce scale dependence

$t\bar{t}$ cross sections (CTEQ6.6, MCFM)

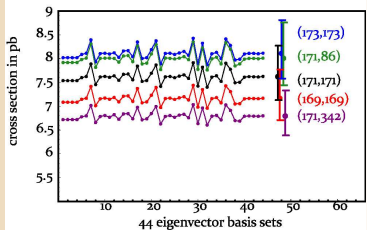
t tbar predictions at Tevatron
CTEQ6.6



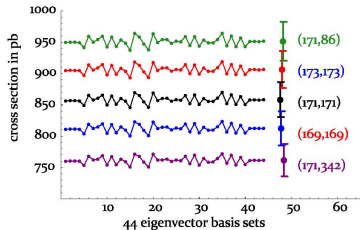
t tbar predictions for LHC
CTEQ6.6



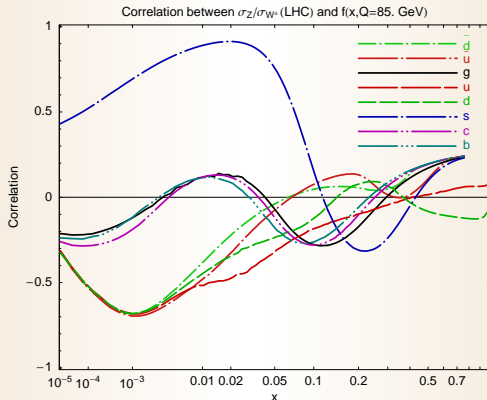
t tbar predictions at Tevatron
CTEQ6.6



t tbar at LHC predictions
CTEQ6.6



σ_Z/σ_W at the LHC



The remaining PDF uncertainty of order $0.5 - 1\%$ in σ_Z/σ_W is mostly driven by $s(x)$; may potentially increase if fixed parameters in existing parametrizations of $s(x)$ are released

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, σ_Z/σ_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