Implications of PDF analysis for collider observables

Pavel Nadolsky

Michigan State University

in collaboration with
Q.-H. Cao, J. Huston, H.-L. Lai, J. Pumplin, D. Stump, W.-K. Tung, C.-P. Yuan

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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)
  - our latest standard PDF set: CTEQ6.6 *(arXiv:0802.0007)*
    - improves on CTEQ6.5 PDF's in several aspects
    - public release of CTEQ6.6 PDF sets is expected very soon
- Focus on applications for the Tevatron and LHC
  - correlation analysis of collider observables **New!**

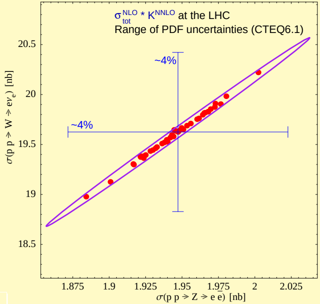
PDF-induced correlations in hadron scattering

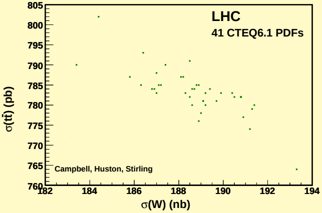
- Dependence on the PDF's is strongly correlated for some pairs of cross sections and anti-correlated for other pairs

  $\Rightarrow$ implications for the monitoring of parton and collider luminosities, determination of new physics parameters

- We examine the origin of the correlations, especially for W, Z, $t\bar{t}$ cross sections, within the CTEQ6.6 theoretical framework

Noteworthy (anti)correlations





CTEQ6.5 global analysis *(Lai, Pumplin, Tung et al.)*

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

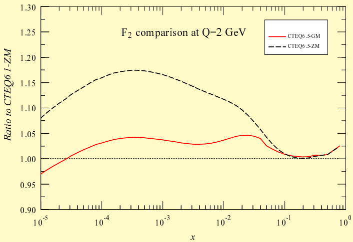
■ full implementation of the general-mass "SACOT-χ" scheme

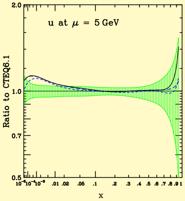
(***Tung et al., hep-ph/0611254***; *Aivasis et al.; Collins, 1998; Kramer, Olness, Soper; Tung, Kretzer, Schmidt; ...*)

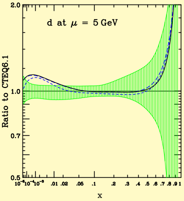
▲ consequences for observables sensitive to c and b quark scattering, especially $F_2^{c,b}(x,Q^2)$

▲ 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 *(Lai, Pumplin, Tung et al.)*

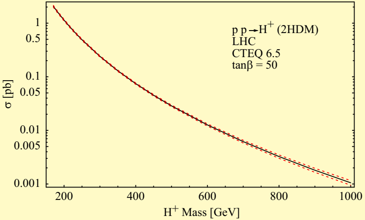
■ a detailed investigation of strangeness degrees of freedom probed by NuTeV and CCFR data *(H.-L. Lai et al., hep-ph/0702268)*

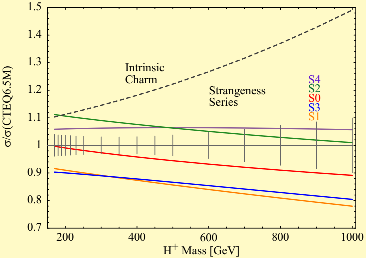
▲ the constraint $\bar{s}(x) \propto \bar{u}(x) + \bar{d}(x)$ for (anti)strangeness PDF's is discarded in favor of independent parametrizations for $s(x)$, $\bar{s}(x)$

▲ 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 $s(x)$ ($p\overset{(-)}{p} \rightarrow W^{+}cX$, $p\overset{(-)}{p} \rightarrow H^{+}_{MSSM}X$)



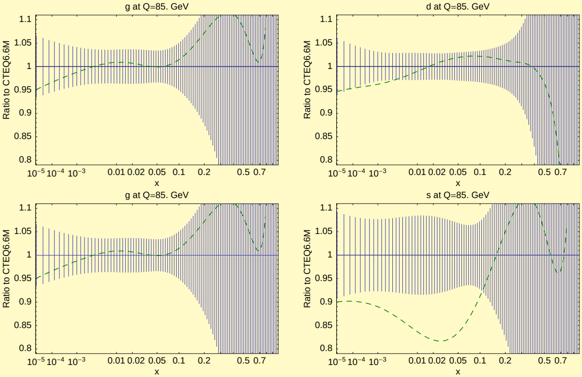


■ A study of "intrinsic charm" scenarios
(J. Pumplin et al., hep-ph/0701220)

Developments since CTEQ6.5 $\Rightarrow$ CTEQ6.6

- NNLO evolution and DIS Wilson coefficients in the SACOT-χ scheme are for the most part implemented
  - public fits still done at NLO
- independent strange PDF's are included in the general-purpose PDF set
- extended x range ($10^{-8} \leq x \leq 1$)
- better agreement with the HERA data on $F_2^{c,b}(x, Q)$
- updated intrinsic charm parametrizations
- Tevatron Run-2 W charge asymmetry (not in CTEQ6.6)

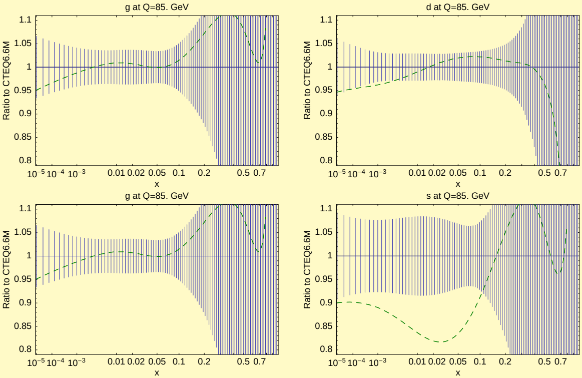
CTEQ6.6 PDF's



dashes: CTEQ6.1M

- CTEQ6.6 *u*, *d* are above CTEQ6.1 by 2-4% at $x \sim 10^{-3}$ at $Q \approx M_Z$
  - The result of suppressed charm contribution to $F_2(x, Q)$ at HERA in the general-mass scheme

CTEQ6.6 PDF's



dashes: CTEQ6.1M

- very different strange PDF's
- constrained by data at $x > 10^{-2}$; depend on assumptions about the flavor structure of quark sea at $x \lesssim 10^{-2}$

Strangeness in the CTEQ6.6 set

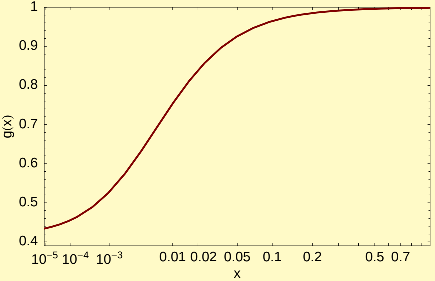
$$s(x) = \bar{s}(x) = A_0 x^{A_1} (1-x)^{A_2} g(x) \text{ at } Q_0 = 1.3 \text{ GeV}$$

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

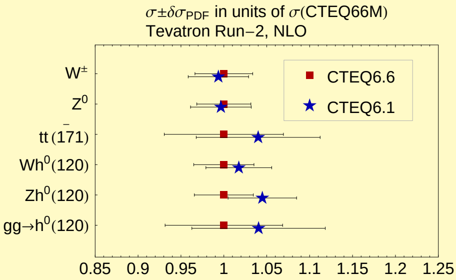
- two new free parameters currently sufficient to describe the data; more would create undesirable flat directions in PDF space
- 22 free PDF parameters (vs. 20 in CTEQ6.1 and 6.5)

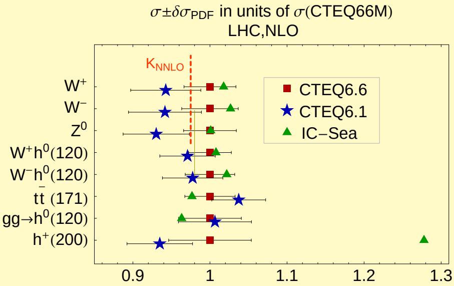
A function $g(x)$ (without free parameters) is chosen to enforce $\bar{s}(x) \approx 0.5\left(\bar{u}(x) + \bar{d}(x)\right)$ at $x \to 0$; $g(x) \to 1$ at $x > 10^{-2}$

χ^2 and crucial collider observables are quite insensitive to the choice of $g(x)$



Tevatron and LHC cross sections





- NLO calculations using ResBos, WTTOT, MCFM
- CTEQ6.5 and CTEQ6.6 cross sections are qualitatively same
- At the LHC, $\sigma_{W,Z}$(CTEQ6.6M)$\approx 1.06\sigma_{W,Z}$(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

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

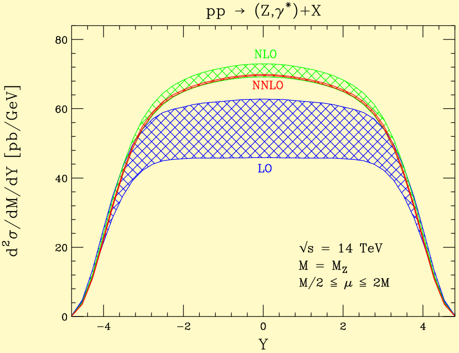
- Event rates for $pp \to W^{\pm}X$, $pp \to Z^0X$ at the LHC can be measured with accuracy $\delta\sigma/\sigma \sim 1\%$ (tens of millions of events even at low luminosity)

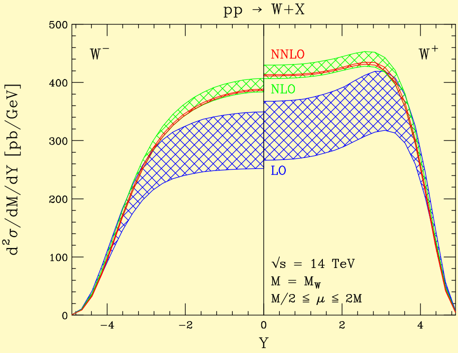
- These measurements will be employed to tightly constrain PDF's and monitor the LHC luminosity $\mathcal{L}$ in real time *(Dittmar, Pauss, Zurcher; Khoze, Martin, Orava, Ryskin; Giele, Keller';...)*
  - other methods will initially give $\delta\mathcal{L} = 10 - 20\%$

- $t\bar{t}$ event rate can be potentially measured with accuracy $\approx 5\%$

W and Z rapidity distributions at NNLO

(Anastasiou, Dixon, Melnikov, Petriello, 2003)



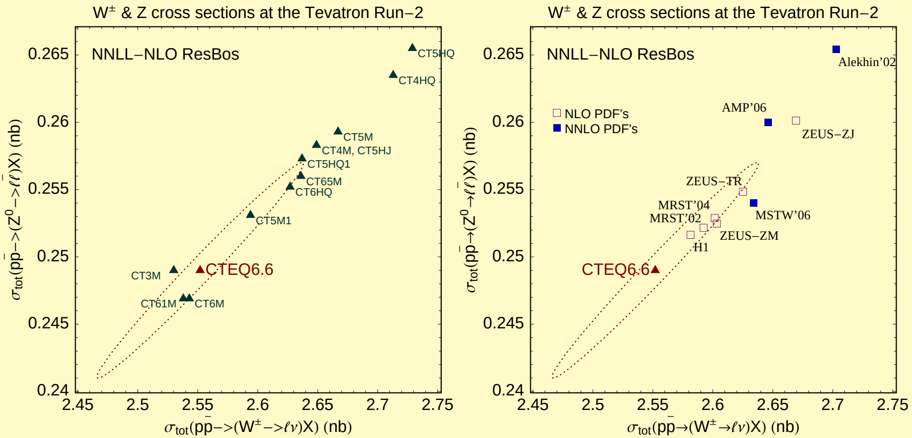


- Tiny scale dependence ($\sim 1\%$)
- For $|y| < 2$, NNLO leads to a uniform rescaling

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

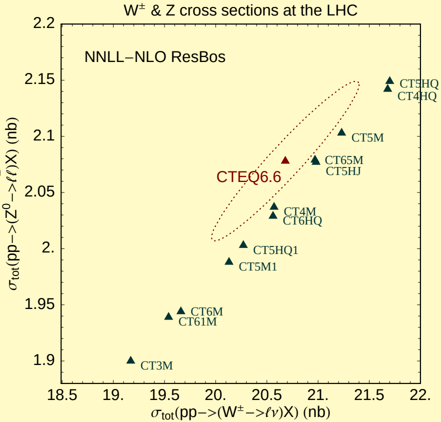
- Larger corrections at forward rapidities

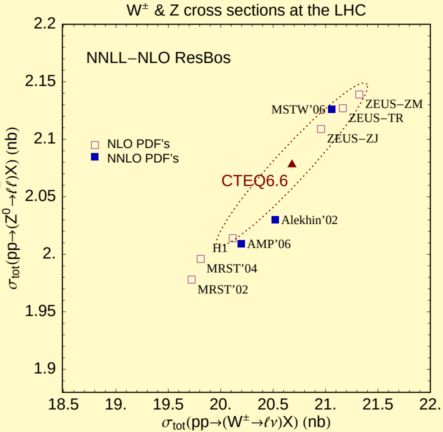
W and *Z* cross sections at the Tevatron



- The ellipse corresponds to $\Delta\chi^2_{scaled} = 100$ (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

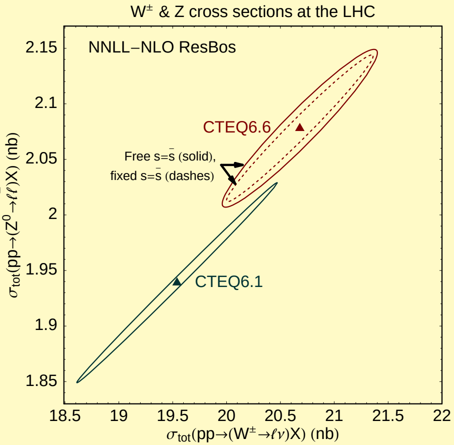
W and *Z* cross sections at the LHC

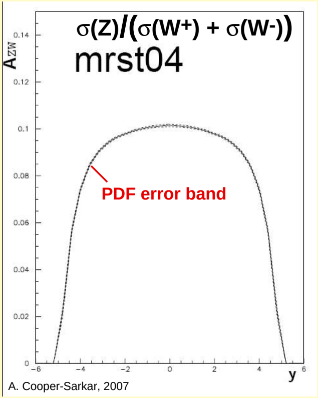




- CTEQ6.6 ellipse is shifted along its minor axis compared to all other CTEQ sets (differences in *s*, *c*, *b* sectors)
- close to predictions based on the MSTW and AMP NNLO PDF's

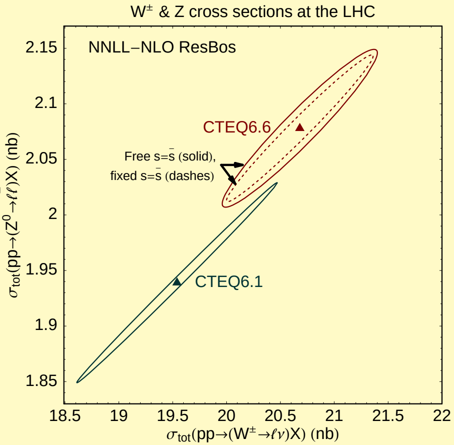
Correlations and ratio of *W* and *Z* cross sections

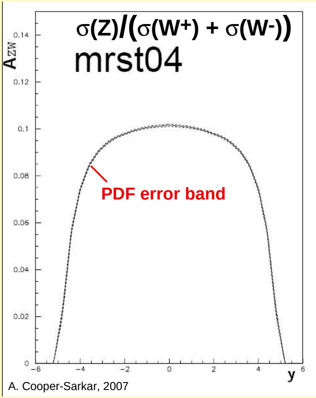




Radiative contributions, PDF dependence have similar structure in *W*, *Z*, and alike cross sections; cancel well in Xsection ratios

Correlations and ratio of W and Z cross sections





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, and σ_Z and $\sigma_{t\bar{t}}$ anti-correlated?
2. Which flavors contribute most of the PDF uncertainty in σ_Z, σ_W?
   - u, d, $\bar{u}$, $\bar{d}$?
   - (large-x) gluons?
   - s, c, b?
3. What is the effect of the (anti)correlations on cross section ratios?

Cross section ratios

- LHC collaborations will normalize many cross sections σ to the "standard candle" cross sections σ_{sc} (i.e., measure $r = \sigma/\sigma_{sc}$)
  - dependence on $\mathcal{L}$ and other systematics may cancel in r
  - PDF uncertainties cancel in r for strongly correlated cross sections; add up in anticorrelated cross sections
- Similar cancellations may occur in $S/\sqrt{B}$, asymmetries, etc.

It helps to find a correlated "standard candle" cross section for each interesting LHC cross section

For example, it is better to normalize σ_{Higgs} to σ_Z ($\sigma_{t\bar{t}}$) if σ_{Higgs} is correlated (anticorrelated) with σ_Z

Correlation analysis of 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 to relate the PDF uncertainty in physical cross sections to PDF's of specific flavors at known (x, μ)

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

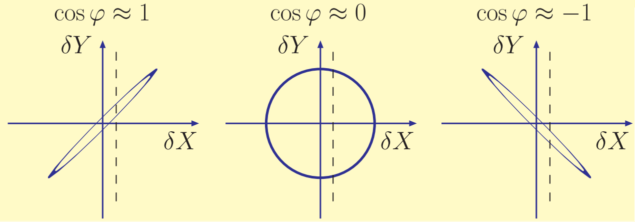
$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)^2}$$

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

Correlation angle φ

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

$$\begin{aligned} X &= X_0 + \Delta X \cos\theta \\ Y &= Y_0 + \Delta Y \cos(\theta + \varphi) \end{aligned}$$



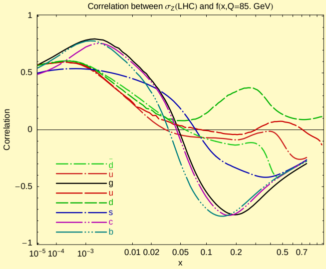
X_0, Y_0: best-fit values

ΔX, ΔY: PDF errors

$\cos\varphi \approx \pm 1$: Measurement of X imposes tight constraints on Y

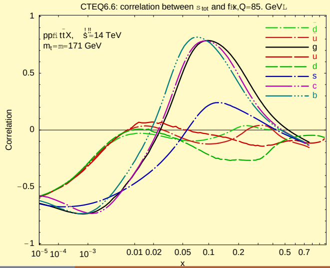
$\cos\varphi \approx 0$: Measurement of X imposes loose constraints on Y

Correlations of Z and $t\bar{t}$ cross sections with PDF's

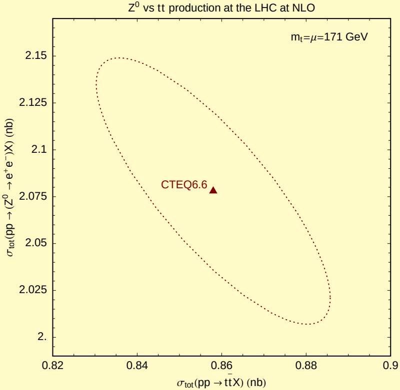


LHC Z, W cross sections are strongly correlated with $g(x)$, $c(x)$, $b(x)$ at $x \sim 0.005$

$\therefore$ 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)

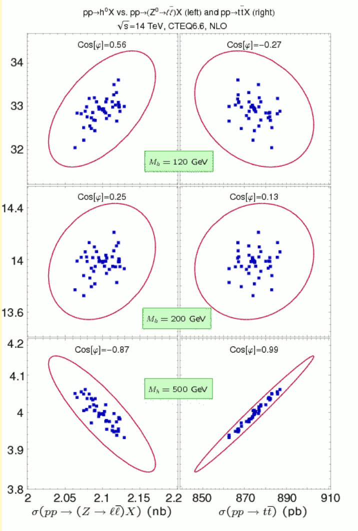


$t\bar{t}$ vs Z cross sections at the LHC



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

Correlations between $\sigma(gg \to H^0)$, σ_Z, $\sigma_{t\bar{t}}$



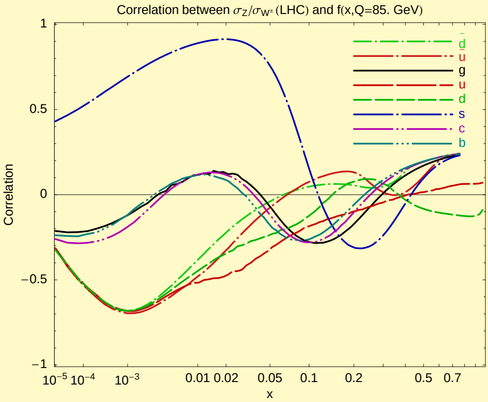
$t\bar{t}$ production as a standard candle process

Uncertainties in $\sigma_{t\bar{t}}$ for $m_t = 171$ GeV

Type	Current	Projected	Assumptions
Scale dependence	11% (NLO)	$\sim 3-5\%$? (NNLO+resum.)	$m_t/2 \le \mu \le 2m_t$
PDF dependence	2%	1%?	1σ c.l.
m_t dependence	5% $\delta m_t = 2$ GeV	$< 3\%$ $\delta m_t = 1$ GeV	
Total (theory)	12%	$\sim 5\%$	
Experiment	8% (CDF)	5%?	

Measurements of $\sigma_{t\bar{t}}$ with accuracy $\sim 5\%$ may be within reach; useful for monitoring of $\mathcal{L}_{LHC}$ in the first years, normalization of cross sections sensitive to large-x glue scattering

σ_Z/σ_W at the LHC



The remaining PDF uncertainty in σ_Z/σ_W is mostly driven by $s(x)$; increases by a factor of 3 compared to CTEQ6.1 as a result of free strangeness in CTEQ6.6

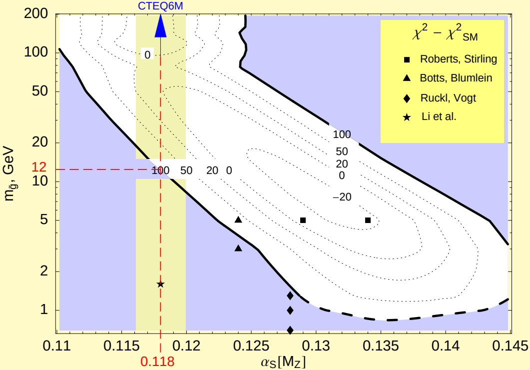
Other developments and ongoing work

- implementation of NNLO contributions and new data sets
  $\Rightarrow$ CTEQ7
- PDF's for Monte-Carlo generators
- combined fit of PDF's and resummed p_T contributions
- nuclear PDF's *(Schienbein, Keppel, Yu, Olness, Owens)*
- updated constraints on gluinos from the PDF analysis *(Berger, PN, Olness)*

Constraints on gluino mass from the PDF analysis

Berger, PN, Olness, Pumplin, 2004

Contour plot for $\delta\chi^2 = \chi^2\left[\alpha_S(M_Z), m_{\tilde{g}}\right] - \chi^2_{\text{CTEQ6M}}$



- $m_{\tilde{g}} > 12$ GeV at $\alpha_s(M_Z) = 0.118$
- lighter gluinos allowed for larger $\alpha_s(M_Z)$
- older fits for $m_{\tilde{g}} < 5$ GeV are excluded

Conclusions

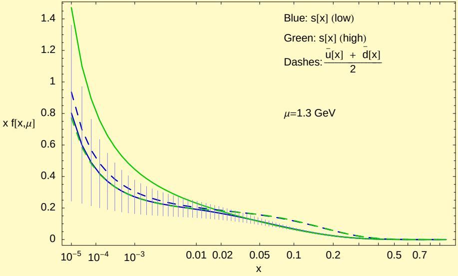
- CTEQ6.6 study confirms most findings of the CTEQ6.5 analyses; predicts some differences in cross sections for heavy-flavor scattering, LHC EW precision physics
- Free parameters in CTEQ6.6 strange PDFs probe a new direction in the PDF parameter space, affect predictions for strange-quark scattering, σ_Z/σ_W at the LHC
- Analysis of correlations in PDF parameter space is a useful 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

Backup slides

Quark flavor (a)symmetry at small x

- For 3 active flavors at $Q_0 = m_c$, the exact $SU(3)_F$ symmetry would imply $\bar{u}(x) = \bar{d}(x) = \bar{s}(x)$ at $x \to 0$

- The actual data allows large violations of $SU(3)_F$ at $x < 10^{-2}$, including solutions with $\bar{s}(x) \approx 1.8\,(\bar{u}(x) + \bar{d}(x))$ at $x \to 0$



- flat direction in the PDF parameter space!

- insignificant effect on the crucial collider observables

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	χ^2(CTEQ6.5M)	χ^2(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