Snapshots of CTEQ-TEA PDF analysis

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CTEQ-Tung Et Al.: ongoing activities

- NLO general-purpose PDF fits
  - CTEQ6.6 set (published in 2008)$\longrightarrow$ CT09 (not released) $\longrightarrow$ CT10 (95% ready for publication)
  - new experimental data, statistical methods, and parametrization forms
  - combined HERA data is included *(next talk by Marco Guzzi)*
- Uncertainty in α_s in the CTEQ PDF analysis *(arXiv:1004.XXXX)*
- Benchmarking of heavy-quark contributions *(backup slides)*
- Constraints on new physics *(talk by Guzzi)*
- PDFs for leading-order Monte-Carlos *(arXiv:0910.4183)*
- Exploration of statistical aspects (data set diagonalization) and PDF parametrization dependence *(Pumplin, arXiv:0909.0268 and 0909.5176)*

CT10 analysis

Experimental data

- Combined HERA-1 neutral-current and charged-current DIS data with 114 correlated systematic effects *(see Guzzi's talk)*
  - replaces 11 separate HERA-1 sets used in the CTEQ6.6 fit
- CDF Run-2 and D0 Run-2 inclusive jet production
- Tevatron Run-2 Z rapidity distributions from both CDF and D0
- W electron asymmetry from CDF II and D0 II; W muon asymmetry from D0 II (CT10W set)
- Other data sets inherited from CTEQ6.6

CT10 analysis

Developments in statistical techniques

- Experimental normalizations N_i are treated on the same footing as other correlated systematic errors
  - Minimum of χ^2 with respect to N_i is found algebraically
  - normalization shifts are automatically accounted for when producing the eigenvector sets
- Set all data weights of 1, unless otherwise specified
  - do not prefer some experiments over the other experiments
  - Exception: NMC/BCDMS and Run-2 W asymmetry data (see below)

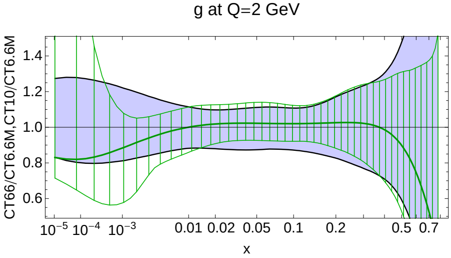
CT10 analysis

Revised functional forms at the input scale

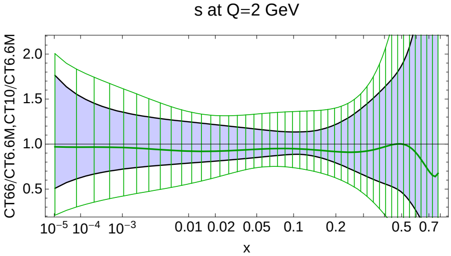
- More data constraints $\Rightarrow$more flexible (=less biased) parametrizations for $g(x, Q_0)$, $d(x, Q_0)$, and $s(x, Q_0)$
- $R_s = \lim_{x\to 0} \left(s(x) + \bar{s}(x)\right) / \left(\bar{u}(x) + \bar{d}(x)\right)$ is not constrained by the data $\Rightarrow$large uncertainty in $s(x)$ at $x \to 0$
  - allow R_s to vary in the fit, but "softly constrain" it by a penalty on χ^2 to satisfy $0.4 < R_s < 1$
- The resulting CT10 error bands overlap with the MSTW/NNPDF bands
- Alternative parametrizations based on Chebyshev polynomials are also explored *(Pumplin, arXiv:0909.5176)*

More flexible parametrizations

CT10(green) vs. CT6.6(blue) ; PRELIMINARY



$g(x, Q)$: large uncertainty at $x < 10^{-3}$, despite tighter constraints by the combined HERA data



$s(x, Q)$: wider uncertainty, covers both CTEQ6.6 and MSTW'08

CT10: agreement between data sets

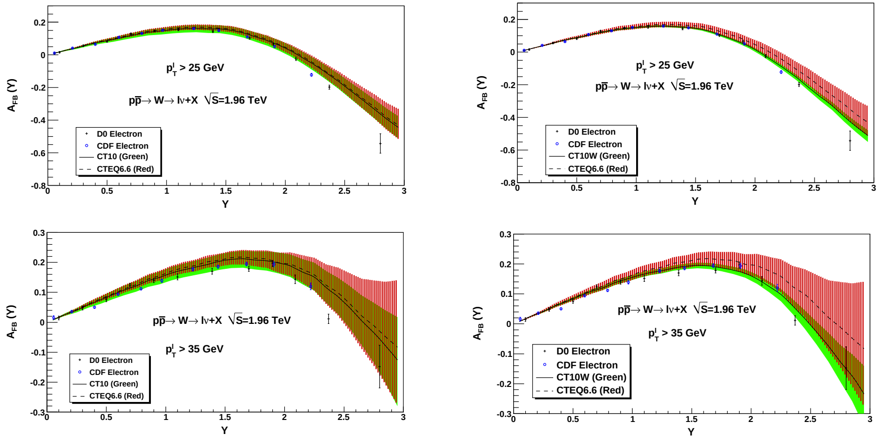
- Good overall agreement: $\chi^2/d.o.f. = 3000/2750 = 1.1$
- Some tensions are also observed:
  - **Tevatron single-inclusive jet production:** Run-1 and Run-2 sets are moderately (in)compatible *(arXiv:0904.2424)*
  - **Tevatron Run-2 W lepton asymmetry**
    - is precise; constrains $d(x)/u(x)$ at $x \to 1$
    - apparently disagrees with constraints on d/u by the NMC and BCDMS muon DIS data
- Two series of PDFs are produced:
  - **CT10:** no Run-2 W asymmetry data are included
  - **CT10W:** with Run-2 W asymmetry, with an extra χ^2 weight
  - **Theoretical cross sections:** computed by ResBos; include the most important part of resummed NNLO corrections

Comparison of CT10 and CT10W fits

- Good fits to electron (e) asymmetry data are possible without NMC and BCDMS; and vice versa
- No acceptable fit to D0 II e asymmetry and NMC/BCDMS data can be achieved, if they are included on the same footing
- Tension between Run-2 e asymmetry and D0 Run-2 μ asymmetry
- Reasonable agreement between Run-2 e W asymmetry data and Z y data
- With special emphasis on D0 II e asymmetry data (χ^2 weight>1), it is possible to obtain a reasonable agreement for W asymmetry ($\chi^2/d.o.f. = 1-2$) , with some remaining tension with NMC & BCDMS $F_2^d(x,Q)$ and $F_2^p(x,Q)$ at $x > 0.4$

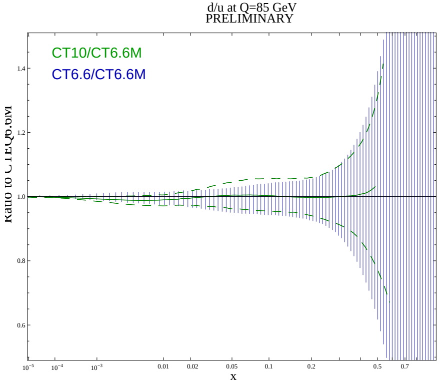
CT10 and CT10W fits with Tevatron Run-2 data

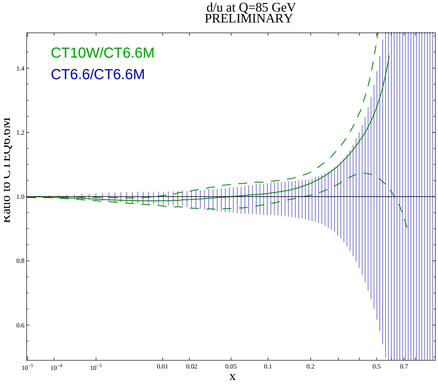
PRELIMINARY



CT10W agrees better with W asy data; has smaller uncertainty than CTEQ6.6 or CT10

$d(x,Q)/u(x,Q)$ at $Q = 85$ GeV

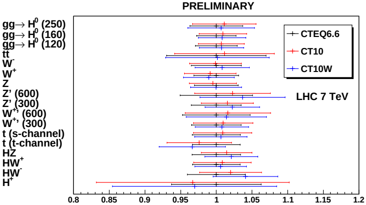


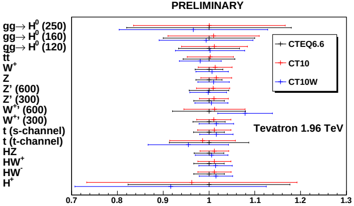


CT10W prefers larger d/u, has smaller uncertainty than CTEQ6.6 or CT10

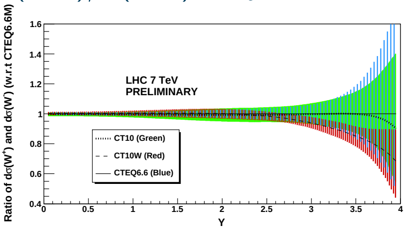
CT10 & CT10W predictions for the LHC & Tevatron

Total cross sections

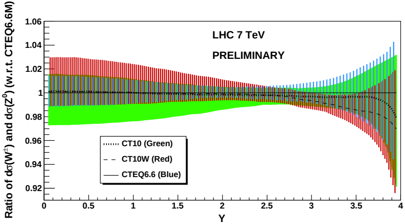




$\sigma(W^+)/\sigma(W^-)$ vs. y_W at the LHC



$\sigma(W^\pm)/\sigma(Z^0)$ vs. $y_{W/Z}$ at the LHC



Uncertainty in α_s in the CTEQ-TEA PDF analysis

arXiv:1004.XXXX – will be posted this week

- Two leading theoretical uncertainties in LHC processes are due to α_s and the PDFs
- These are not independent uncertainties; how can one quantify their correlation?
- Which central $\alpha_s(M_Z)$ and which error on $\alpha_s(M_Z)$ are to be used with the existing PDFs?
- What are the consequences for key LHC processes ($gg \to H^0$, etc.)?

Uncertainty in α_s in the CTEQ-TEA PDF analysis

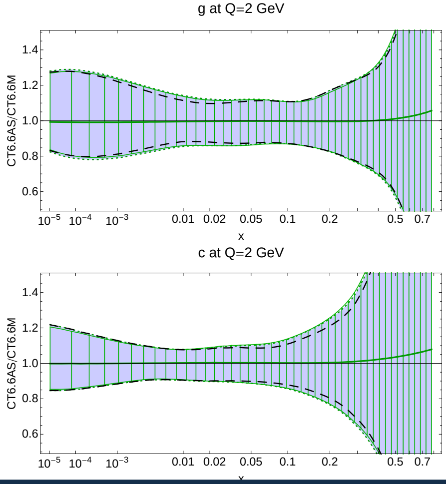
arXiv:1004.XXXX – will be posted this week

Recent activity to examine these questions, e.g.:

- **MSTW** *(arXiv:0905.3531)*
  - $\alpha_s(M_Z)$ is an **output** of the global fit (constrained by the hadronic scattering only)
  - several sets of error PDFs, each with its own $\alpha_s(M_Z)$ value $\Rightarrow$ lengthier calculations
  - The α_s uncertainty and PDF uncertainty are inseparable
- **NNPDF** *(in 2009 Les Houches Proceedings, arXiv:1004.0962)*:
  - $\alpha_s(M_Z) = 0.119 \pm 0.002$ is taken as an **input**
  - α_s-PDF correlation is examined with ~ 1000 PDF replicas and found to be small
- **H1+ZEUS** *(arXiv:0911.0884)*: sensitivity of the HERAPDF set to $\delta\alpha_s(M_Z) = \pm 0.002$ is explored

Our findings

Total PDF+α_s errors ΔX are the **same** when found (a) from a full fit with floating α_s, or (b) by adding ΔX_{PDF} and ΔX_{α_s} in quadrature

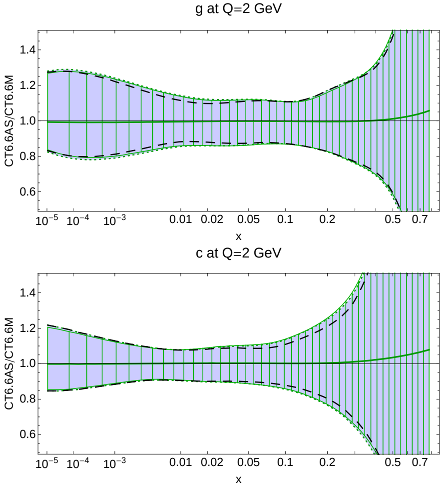


- black – CTEQ6.6 PDF uncertainty
- Blue filled – PDF+α_s uncertainty of the fit with floating $\alpha_s(M_Z)$
- Green hatched – PDF+α_s uncertainty added in quadrature

Also, agreement in cross section predictions $\Rightarrow$ backup slides

Our findings

Total PDF+α_s errors ΔX are the same if found either from a full fit with floating α_s, or by adding ΔX_{PDF} and ΔX_{α_s} in quadrature



This agreement is **a rigorous consequence** of the quadratic approximation

Details of the CTEQ6.6FAS analysis

- Take the "world-average" $\alpha_s(M_Z) = 0.118 \pm 0.002$ as an **input**:

$$\alpha_s(M_Z)|_{\text{in}} = 0.118 \pm 0.002 \text{ at } 90\% \text{ C.L.}$$

- Find the theory parameter $\alpha_s(M_Z)$ as an **output** of a global fit (CTEQ6.6FAS):

$$\alpha_s(M_Z)|_{\text{out}} = 0.118 \pm 0.0019 \text{ at } 90\% \text{ C.L.}$$

- The combined PDF+α_s uncertainty is estimated as

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{22+1}\left(X_i^{(+)} - X_i^{(-)}\right)^2}$$

- **Problem:** each PDF set comes with its own $\alpha_s \Rightarrow$ cumbersome
- **A simple workaround exists!**

A quadrature sum reproduces the α_s-PDF correlation
H.-L. Lai, J. Pumplin

Theorem

In the quadratic approximation, the total α_s+PDF uncertainty $\Delta\sigma$ of the CTEQ6.6FAS set, with all correlation, reduces to

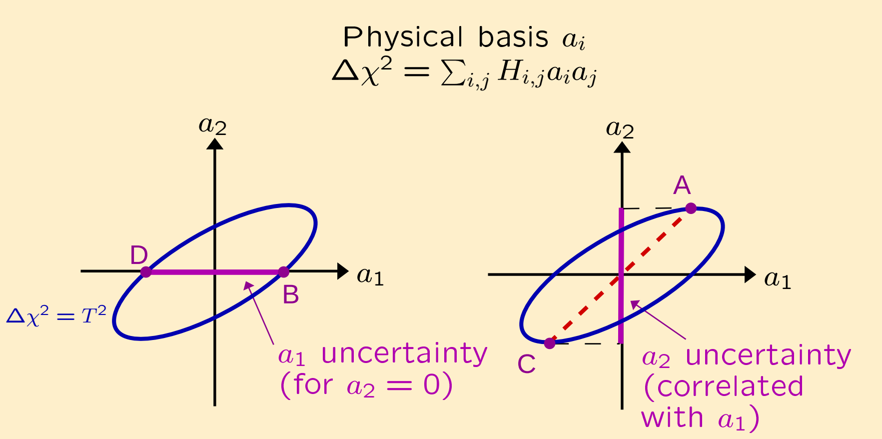
$$\Delta X = \sqrt{\Delta X^2_{CTEQ6.6} + \Delta X^2_{\alpha_s}},$$

where

- $\Delta X_{CTEQ6.6}$ *is the CTEQ6.6 PDF uncertainty from 44 PDFs with the same* $\alpha_s(M_Z) = 0.118$
- $\Delta X_{\alpha_s} = (X_{0.120} - X_{0.116})/2$ *is the* α_s *uncertainty computed with two central CTEQ6.6AS PDFs for* $\alpha_s(M_Z) = 0.116$ *and* 0.120

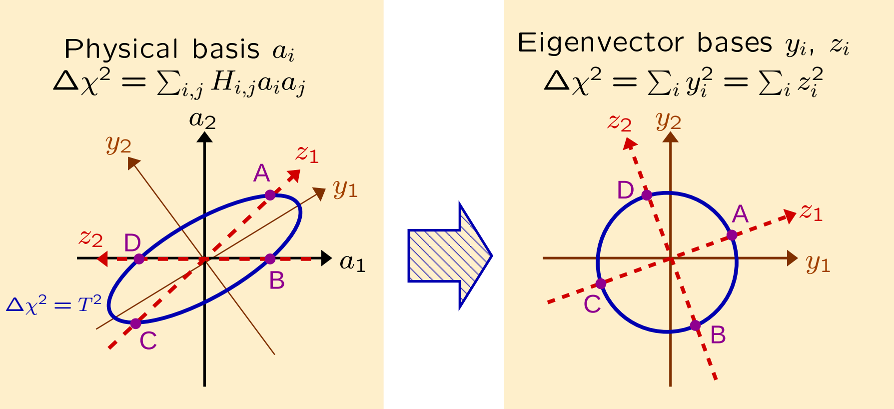
The full proof is given in the paper; the main idea is illustrated for 1 PDF parameter a_1 and α_s parameter a_2

Illustration of the theorem for 2 parameters



$$\Delta X_1^2 = \frac{1}{4}\left(X(B) - X(D)\right)^2 \qquad \Delta X_2^2 = \frac{1}{4}\left(X(A) - X(C)\right)^2$$

Illustration of the theorem for 2 parameters, cont.



$$\Delta X^2 = \frac{1}{4}\left[(X(A) - X(C))^2 + (X(B) - X(D))^2\right]$$
$$= \Delta X_1^2 + \Delta X_2^2$$

Summary I

Tevatron Run-2 W asymmetry data...

...become increasingly complete and precise (measurements by both CDF and D0; electron and muon channels)

...cannot be explained based on the d/u ratio found from the low-Q DIS data (mostly NMC and BCDMS)

- Several cross checks of the theoretical calculation for W asymmetry (resummed NNLL+partial NNLO in ResBos); no problems were found
- Higher-twist and nuclear corrections in the large-x BCDMS/NMC deuterium data are the usual suspects

  (Virchaux and Milsztajn; Alekhin; Accardi et al.)
- CT10 and CT10W sets of PDFs for practical applications, without and with constraints from the Run-2 W asymmetry

Summary II

CTEQ6.6AS PDF sets (available in the LHAPDF library):

- from 4 alternative CTEQ6.6 fits for

$$\alpha_s(M_Z) = 0.116, 0.117, 0.119,\ 0.120$$

- sufficient to compute uncertainty in $\alpha_s(M_Z)$ at $\approx$68% and 90% C. L., including **the world-average** $\alpha_s(M_Z) = 0.118 \pm 0.002$ as an **input data point**
- **The CTEQ6.6AS** α_s uncertainty should be combined with the CTEQ6.6 PDF uncertainty as

$$\Delta X = \sqrt{\Delta X^2_{CTEQ6.6} + \Delta X^2_{CTEQ6.6AS}}$$

- The total uncertainty ΔX reproduces the full correlation between $\alpha_s(M_Z)$ and PDFs

Backup slides

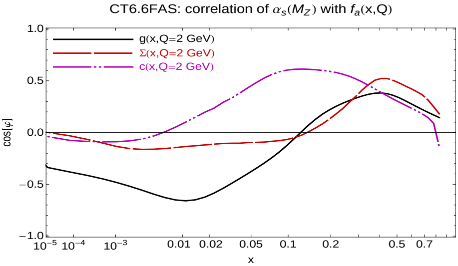
Full and reduced fits with variable α_s: cross sections

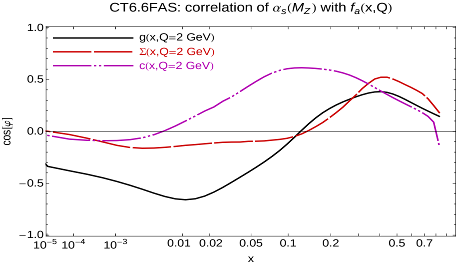
Process	CTEQ6.6+CTEQ6.6AS				CTEQ6.6FAS
$t\bar{t}$ (171 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
LHC 7 TeV	157.41	10.97	7.54	13.31	160.10 ± 13.93
LHC 10 TeV	396.50	18.75	16.10	24.71	400.48 ± 25.74
LHC 14 TeV	877.19	28.79	30.78	42.15	881.62 ± 44.27
$gg \to H$ (120 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.63	0.042	0.032	0.053	0.64 ± 0.055
LHC 7 TeV	10.70	0.31	0.32	0.45	10.70 ± 0.48
LHC 10 TeV	20.33	0.66	0.56	0.87	20.28 ± 0.93
LHC 14 TeV	35.75	1.31	0.94	1.61	35.63 ± 1.70
$gg \to H$ (160 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.26	0.026	0.015	0.030	0.26 ± 0.031
LHC 7 TeV	5.86	0.16	0.18	0.24	5.88 ± 0.26
LHC 10 TeV	11.73	0.33	0.33	0.47	11.72 ± 0.50
LHC 14 TeV	21.48	0.68	0.56	0.88	21.43 ± 0.94
$gg \to H$ (250 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.055	0.0099	0.0044	0.011	0.058 ± 0.012
LHC 7 TeV	2.30	0.085	0.081	0.12	2.32 ± 0.12
LHC 10 TeV	5.08	0.14	0.15	0.21	5.10 ± 0.22
LHC 14 TeV	10.03	0.26	0.27	0.37	10.04 ± 0.41

The full and reduced methods perfectly agree

Correlation cosine between CTEQ6.6FAS PDFs and $\alpha_s(M_Z)$

Based on the method in the CTEQ6.6 paper, PRD 78, 013004 (2008)





$$\cos\varphi = \frac{1}{4\Delta X \Delta Y} \times \sum_{i=1}^{23} \left[\left(X_i^{(+)} - X_i^{(-)} \right) \left(Y_i^{(+)} - Y_i^{(-)} \right) \right]$$

Variations in $\alpha_s(M_Z)$ mostly affect:

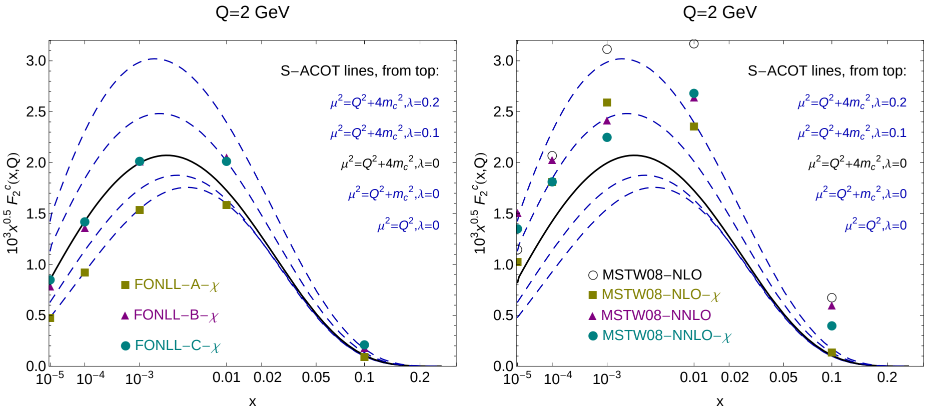
- $g(x,Q)$ at $x \approx 0.01$
- $c(x,Q)$ at $x \approx 0.1$
- Singlet quark at $x \approx 0.5$

Les Houches benchmarks for heavy-quark cross sections

arXiv:1003.1241

- CTEQ-TEA participates in the comparison of QCD calculations for heavy-quark SIDIS at the 2009 Les Houches workshop
- A set of benchmarks is provided based on the comparison of several general-mass schemes (ACOT, Thorne-Roberts, FONLL...)
- CTEQ-TEA implementation of the S-ACOT-χ scheme agrees well with an alternative realization of this scheme by the FONLL-A-χ approach *(Forte, Laenen, Nason, and Rojo)*

$F_2^c(x, Q)$: S-ACOT-χ, FONLL, and MSTW predictions



- Black solid: for our default scale μ and rescaling variable χ
- $\lambda = 0.1$ or 0.2: for generalized rescaling variable $\zeta(\lambda)$ from

P.N. and Tung, arXiv:0903.2667

- FONLL and MSTW predictions are for $\mu^2 = Q^2$