QCD for Collider Physics

Part 4

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Parton density fits

Parton densities involve QCD at low momentum scales $\leftrightarrow$ large coupling

- can compute $\partial f(x,\mu)/\partial\mu$ in perturbation theory, but not $f(x,\mu)$
- ongoing effort to compute with non-perturbative methods
  e.g. in lattice QCD
- in practice: determined from experimental data

Principle of PDF determinations:

- data for observables with factorisation formulae
  most important: DIS ($ep \to e + X$), Drell-Yan ($pp \to \ell^+\ell^- + X$, $pp \to \ell\nu + X$), jets in ep and pp, $t\bar{t}$ production in pp, ...
- parameterise PDFs at "starting" scale μ_0
  use DGLAP eqs. to evolve to scales μ needed in fact. formulae
- determine PDF parameters by fit to data

Uncertainties on extracted PDFs

"PDF errors"

- errors (stat. and syst.) of fitted data propagated to PDF parameters

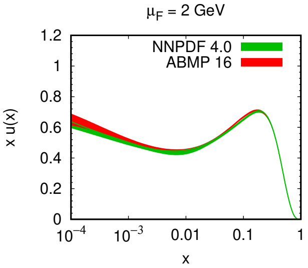
"systematic theory uncertainties"

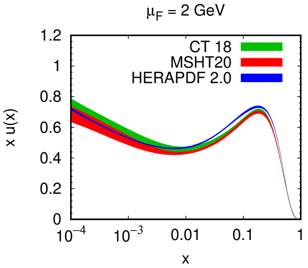
- selection of data sets and kinematics
- perturbative order of evolution and hard-scattering cross sections
- values of α_s and m_c, m_b and possibly other constants
  if taken as external parameters rather than fitted
- fine details of perturbative calculations
  e.g. treatment of heavy quarks, resummation
- power corrections (try to avoid by using data with $Q > Q_{\mathsf{min}}$)

recent work: include uncertainties from higher orders in PDF errors

Harland-Lang, Thorne 2018; Khalek et al. 2019; McGowan et al. 2023

Illustration of PDF sets and their errors

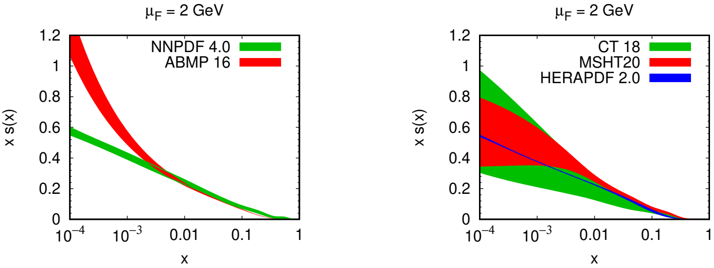




all PDFs at NNLO, error bands for 68% CL

- spread between different parameterisation often larger than error bands of single parameterisation
- error bands propagate uncertainties of fitted data into PDFs but do not reflect "systematic theory uncertainties" of extraction

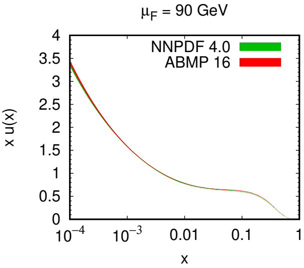
Illustration of PDF sets and their errors

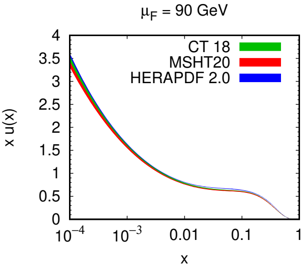


all PDFs at NNLO, error bands for 68% CL

- strangeness distribution remains poorly known
  sometimes assume $s(x) \propto \bar{u}(x) + \bar{d}(x)$ or $s(x) \propto \bar{d}(x)$ at $\mu = \mu_0$
  $\rightsquigarrow$ small errors in fit

Illustration of PDF sets and their errors

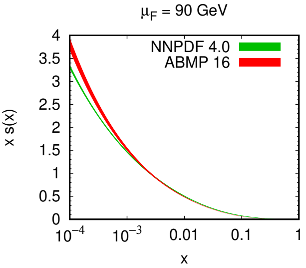


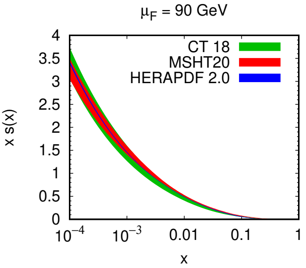


all PDFs at NNLO, error bands for 68% CL

- evolution to higher scales $\rightsquigarrow$ $q\bar{q}$ pairs at low x

Illustration of PDF sets and their errors

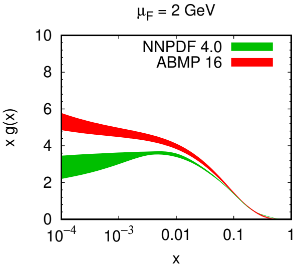


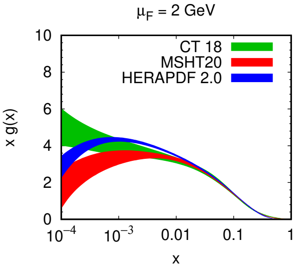


all PDFs at NNLO, error bands for 68% CL

- evolution to higher scales $\rightsquigarrow$ $q\bar{q}$ pairs at low x
- all $q(x)$ and $\bar{q}(x)$ become similar at high scales and low x
- relative uncertainties shrink

Illustration of PDF sets and their errors

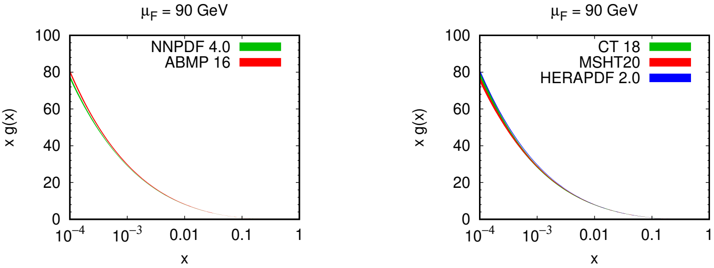




all PDFs at NNLO, error bands for 68% CL

- $g(x) \gg q(x)$ for x below 0.1
- at low scale and low x gluon known very poorly

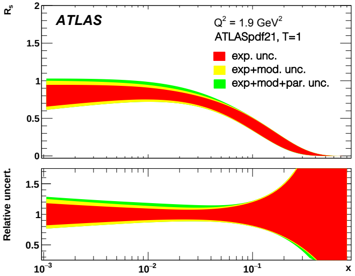
Illustration of PDF sets and their errors



all PDFs at NNLO, error bands for 68% CL

- $g(x) \gg q(x)$ for x below 0.1
- evolution for $g(x)$ even stronger than for $q(x)$

Strange quarks: recent results



ratio of strange to non-strange sea quarks:

$$R_s(x) = \frac{s(x) + \bar{s}(x)}{\bar{u}(x) + \bar{d}(x)}$$

ATLAS, arXiv:2112.11266