QCD

Part 4

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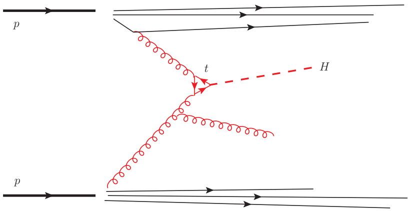
And now for something completely different

a few words about general-purpose event generators
e.g. Herwig, Pythia, Sherpa

note: Many other generators exist, often with a specialised scope and approach. Not all of them fit the description given in the following.

Monte Carlo generators e.g. Herwig, Pythia, Sherpa

- build on structure of factorisation formulae e.g. for $pp \to H + g + X$
- but compute fully specified events, i.e. no "$+X$"
  schematically:



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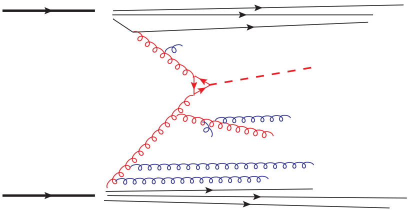

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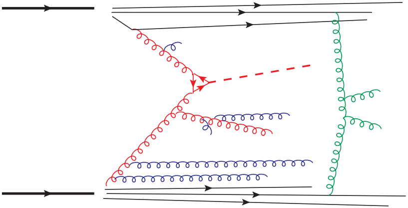

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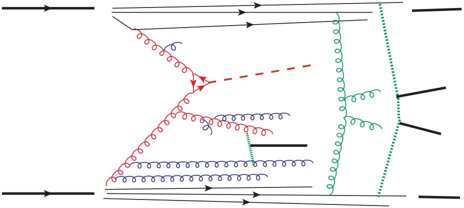

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  - models for multiparton interactions and hadronisation

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

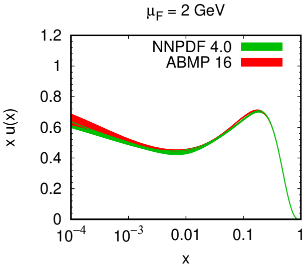
“systematic theory uncertainties”

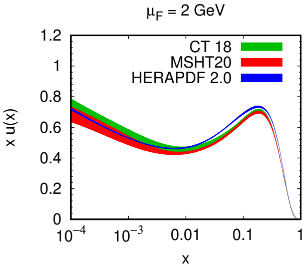
- selection of data sets and kinematics
- perturbative order of evolution and hard-scattering cross sections
- values of α_s and m_c, m_b and possibly other constants
  if they are taken as external parameters rather than fitted
- fine details of perturbative calculations
  e.g. treatment of heavy quarks,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

ongoing effort: 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

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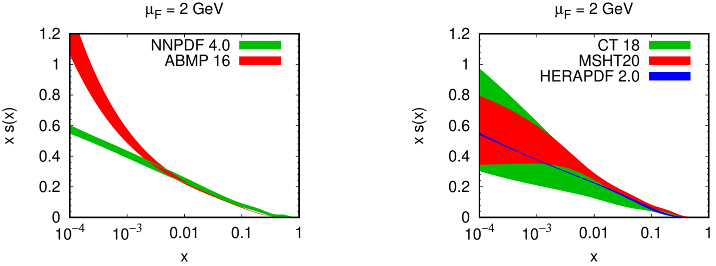

all PDFs at NNLO, error bands for 68% CL

- 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

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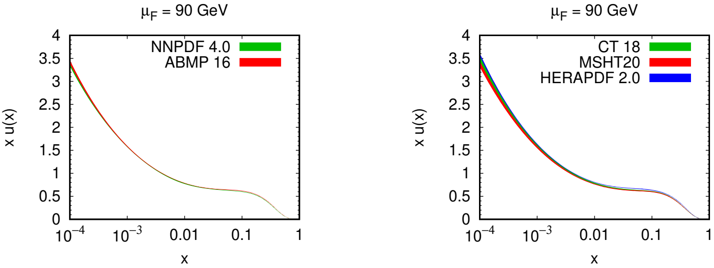

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- evolution to higher scales $\rightsquigarrow$ $q\bar{q}$ pairs at low x

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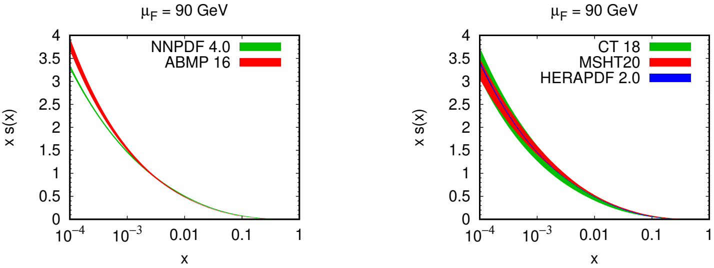

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- evolution to higher scales $\rightsquigarrow$ $q\bar{q}$ pairs at low x
- all $q(x)$ and $\bar{q}(x)$ become similar at high scales and low x
- relative uncertainties shrink

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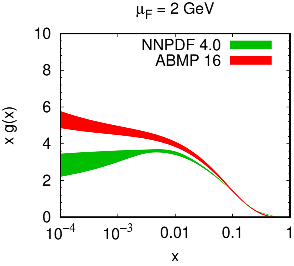

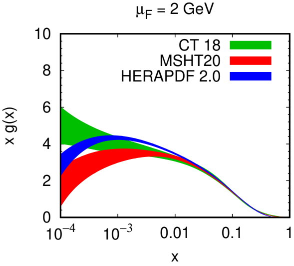

all PDFs at NNLO, error bands for 68% CL

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

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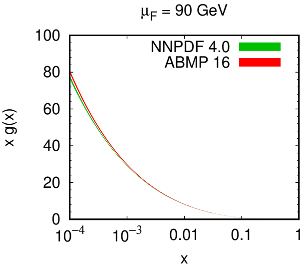
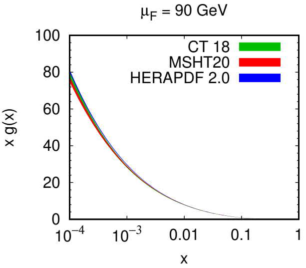
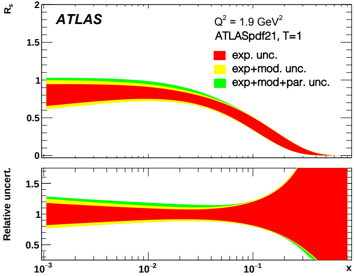




all PDFs at NNLO, error bands for 68% CL

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

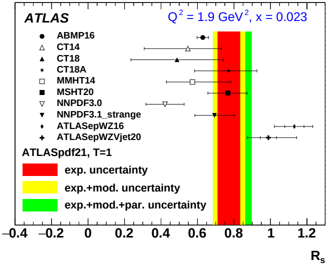
Strange quarks: recent results

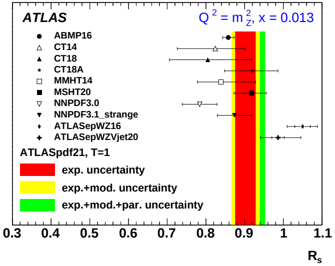


ratio of strange to non-strange sea quarks:

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

ATLAS, arXiv:2112.11266





Instead of a summary: