

# QCD Theory

## 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 ( $ep \rightarrow e + X$ ), Drell-Yan ( $pp \rightarrow \ell^+ \ell^- + X$ ,  
 $pp \rightarrow \ell\nu + X$ ), jet production in  $ep$  and  $pp$ , ...
- ▶ specify PDF at “starting” scale  $\mu_0$   
use DGLAP eqs. to evolve to scales  $\mu$  needed in fact. formulae
- ▶ parameterise PDFs at  $\mu_0$  and determine parameters by fit to data

## Uncertainties on extracted PDFs

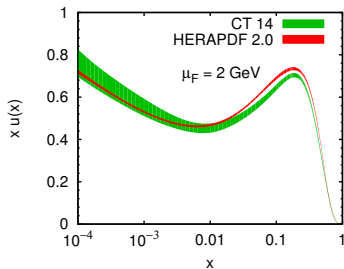
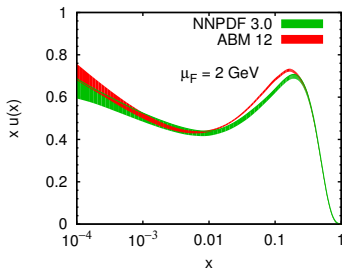
### “PDF errors”

- ▶ errors (stat. and syst.) of fitted data propagated to parameters describing PDFs

### “systematic theory uncertainties”

- ▶ selection of data sets and kinematics
- ▶ perturbative order of evolution and hard-scattering coefficients
- ▶ values of  $\alpha_s$  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  $Q > Q_{\min}$ )**
- ▶ ...

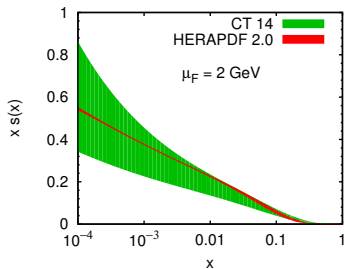
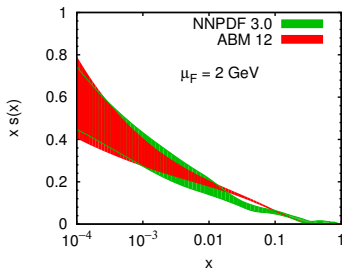
## Illustration of PDF sets and their errors



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

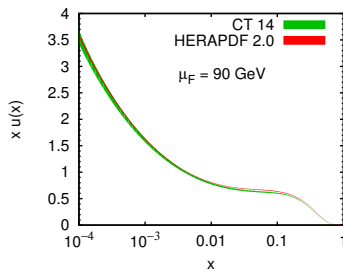
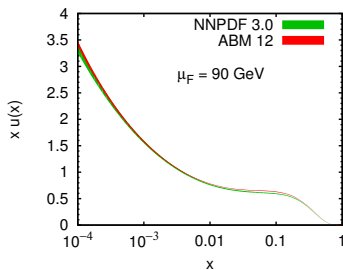
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- ▶ strangeness distribution remains poorly known  
sometimes assume  $s(x) \propto \bar{u}(x) + \bar{d}(x)$  or  $s(x) \propto \bar{d}(x)$  at  $\mu = \mu_0$   
 $\rightsquigarrow$  small errors in fit

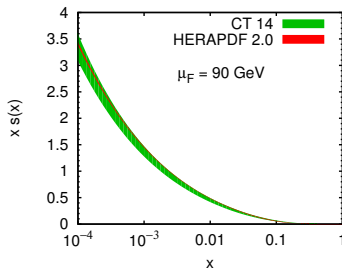
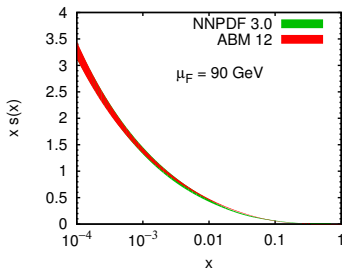
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- ▶ evolution to higher scales  $\rightsquigarrow$   $q\bar{q}$  pairs at low  $x$

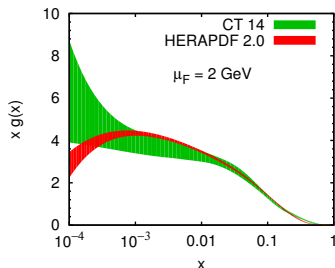
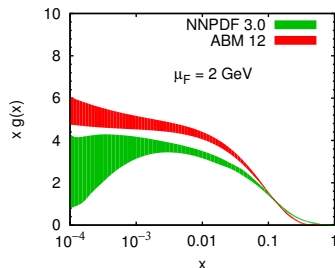
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- ▶ evolution to higher scales  $\rightsquigarrow q\bar{q}$  pairs at low  $x$
- ▶ all  $q(x)$  and  $\bar{q}(x)$  become similar at high scales and low  $x$
- ▶ relative uncertainties shrink

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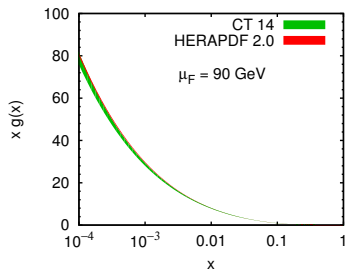
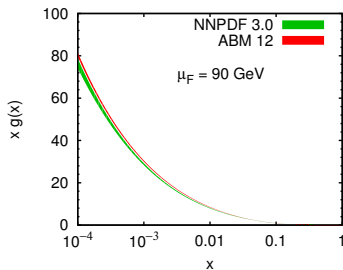


all PDFs at NNLO, error bands for 68% CL

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



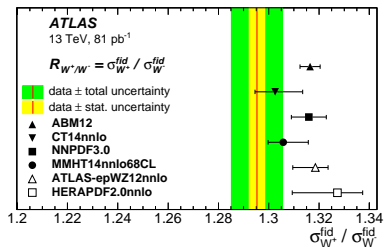
## Illustration of PDF sets and their errors



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

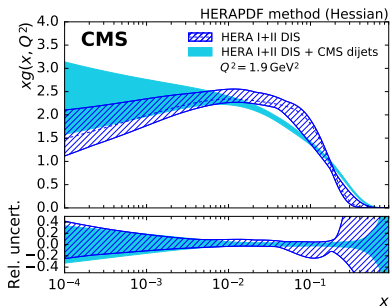
## PDFs and LHC data



$W^+$  and  $W^-$  production

$\sqrt{s} = 13 \text{ GeV}, 81 \text{ pb}^{-1}$

ATLAS, arXiv:1603.09222



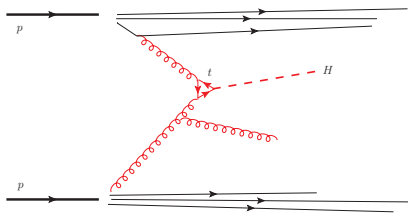
dijet production

$\sqrt{s} = 8 \text{ GeV}, 19.7 \text{ fb}^{-1}$

CMS, arXiv:1705.02628

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

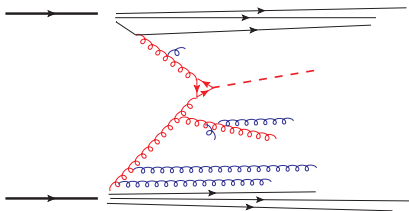
- ▶ build on structure of factorisation formulae e.g. for  $pp \rightarrow H + g + X$
- ▶ but compute fully specified events, i.e. no “+X” schematically:



- ▶ ingredients:
  - parton densities and hard-scattering matrix elements

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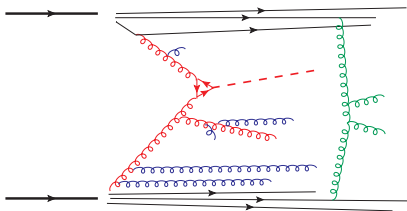
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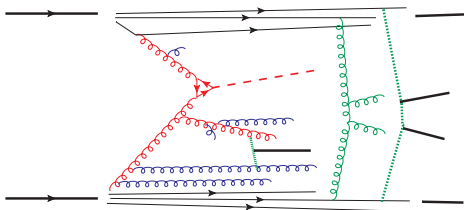
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- ▶ ingredients:
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  - parton showers: small-angle radiation from partons in initial and final state (in perturbative region)
  - models for multiparton interactions and hadronisation

# Instead of a summary

## Standard Model Total Production Cross Section Measurements

Status:  
July 2017

