Nucleon PDF separation with the collider and fixed-target data

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- Theory: NNLO CC at $Q >> m_c$
- Strange sea
  - NOMAD and CHORUS fixed-target data
  - CMS and ATLAS $W$+charm data
- Non-strange quarks
  - CMS charged-lepton asymmetry
  - D0 charged-lepton and $W$ asymmetry

ICHEP2014, Valencia, 4 Jul 2014
The ABM fit ingredients

DATA:
- DIS NC inclusive
- DIS charm production
- DIS $\mu\mu$ CC production (NOMAD data)
- DIS charmed-hadron CC production (CHORUS data)
- fixed-target DY
- LHC DY distributions (CMS 4.7 1/fb)
- W+charm production (CMS and ATLAS data)

QCD:
- NNLO evolution
- NNLO massless DIS and DY coefficient functions
- NLO+ massive DIS coefficient functions (**FFN scheme**)
  - NLO + NNLO threshold corrections for NC
  - NNLO CC at $Q>> m_c$
  - running mass
- NNLO exclusive DY (DYNLO 1.3 / FEWZ 3.1)
- NNLO inclusive ttbar production (pole / running mass)

Deuteron corrections in DIS:
- Fermi motion
- off-shell effects

Power corrections in DIS:
- target mass effects
- dynamical twist-4 terms

The jet data are still not included: The NNLO corrections may be as big as 15-20%

ABM12: sa, Blümlein, Moch PRD 89, 054028 (2014)
Asymptotic NNLO CC corrections at $Q \gg m_c$ relevant for the HERA kinematics

- Effect is $\sim 5\%$ at small $x$

- $\Delta X^2 = -6/114$ for the HERA RunI CC data; bigger impact for RunII expected

Buza van Neerven, NPB 500, 301 (1997)
Blümlein, Hasselhuhn, Pfoh NP B881, 1 (2014)
The semi-leptonic branching ratio $B_\mu$ is a bottleneck

- weighted average of the charmed-hadron rates

$$B_\mu(E_\nu) = \sum h r^h(E_\nu) B^h_\mu = a/(1+b/E_\nu)$$

- fitted simultaneously with the PDFs, etc. using the constraint from the emulsion data
CHORUS charm data in the ABM fit

Emulsion data on charm/CC ratio with the charmed hadron vertex measured

– full phase space measurements
– no sensitivity to $B_\mu$
– low statistics (2013 events)

CHORUS data pull strangeness up, however the statistical significance of the effect is poor
CMS W+charm data in the ABM fit

CMS data go above the NuTeV/CCFR by $1\sigma$; little impact on the strange sea.

The charge asymmetry is in a good agreement with the charge-symmetric strange sea.

Good agreement with the CHORUS data.
ATLAS W+charm data in the ABM fit

ATLAS Collaboration arXiv:1402.6263
Strange sea preferred by different data combination

- NOMAD+CHORUS do not go far from NuTeV/CCFR; improved strangeness accuracy
- CHORUS+CMS+ATLAS differ from NuTeV/CCFR+NOMAD by 2-3σ at x~0.1 (upper margin of the data tension)
- Largest-η ATLAS bin pulls strangeness up by 1σ – edge effect?
Nominal ABM update (NuTeV/CCFR+NOMAD+CHORUS) demonstrate good agreement with the CMS results.

The ATLAS strange-sea is enhanced, however it is correlated with the d-quark sea suppression → disagreement with the FNAL-E-866 data.

Upper margin of the ABM analysis (CHORUS+CMS+ATLAS) is still lower than ATLAS.

Integral strangeness suppression factor $\kappa_s (20 \text{ GeV}^2)=0.654(30)$.
Comparison with recent DY LHC data

CMS (7 TeV, 4.7 1/fb)

- Improved accuracy of predictions for the charged-lepton asymmetry (7000h of DYNNLO to get a smooth curve!)
- Good agreement with the updated CMS data
  
  $P_T > 25 \text{ GeV}$, $> 35 \text{ GeV}$
  
  $X^2 = 16, 11$ for NDP=11
  
  Further improvement in d-u separation

CMS Collaboration hep-ex/1312.6283
Comparison with recent DY Tevatron data

D0 (1.96 TeV, 7.3 1/fb)

- Poor agreement with the ABM12 predictions at $P_T > 35$ GeV

- Poor description in the fit: $\chi^2 = 40/10$ and $19/10$ for $P_T > 35$ and 25, respectively

- Polynomial fit gives $\chi^2 = 11/10$, however displays a step structure at $Y \sim 1$

- Smooth shape is observed in case of electron
Summary

- Improved accuracy of strange sea using NOMAD and CHORUS data, factor of 2 at $x \sim 0.1$

- Enhancement of ~20% due to CHORUS, CMS, and ATLAS data
  - statistical fluctuation?
  - impact of the NNLO corrections on $W+\text{charm}$ production?
  - problems in $B_\mu$ or fragmentation model?

- The ATLAS and NNPDF2.3 $\text{coll}_\text{strangeness}$ determinations go above the ABM one due to suppression of the $d$-quark sea → separation of the quark species using only the collider data still has strong limitations

- Good agreement with the recent CMS data → further improvement in the $d-u$ separation

- Poor agreement with the recent D0 data → clarification is necessary
Extras
Impact of the LHC DY data on the PDFs

- $d$-quarks increase at $x \approx 0.1$; the errors get smaller
- non-strange sea decrease at $x \approx 0.1$
- strange sea stable → the enhancement observed by ATLAS is not reproduced

*The algorithm used to include the LHC data is quite stable*
Impact of the separate LHC data sets

The biggest effect come from the LHCb data, i.e. from the large rapidity region.
NNLO DY corrections in the fit

The (N)NLO calculations are quite time-consuming → fast tools are employed (FASTNLO, Applegrid,.....)

– the corrections for certain basis of PDFs are stored in the grid
– the fitted PDFs are expanded over the basis
– the NNLO c.s. in the PDF fit is calculated as a combination of expansion coefficients with the pre-prepared grids

The general PDF basis is not necessary since the PDFs are already constrained by the data, which do not require involved computations → use as a PDF basis the eigenvalue PDF sets obtained in the earlier version of the fit

\[ P_0 \pm \Delta P_0 \] – vector of PDF parameters with errors obtained in the earlier fit
\[ E \] – error matrix
\[ P \] – current value of the PDF parameters in the fit

– store the DY NNLO c.s. for all PDF sets defined by the eigenvectors of \( E \)
– the variation of the fitted PDF parameters \( (P - P_0) \) is transformed into this eigenvector basis
– the NNLO c.s. in the PDF fit is calculated as a combination of transformed \( (P - P_0) \) with the stored eigenvector values
Value of $\alpha_s$ in/from the PDF fits

- The Tevatron jet data push $\alpha_s$ up by $\sim 0.001$

- The MSTW and NNPDF values are bigger than the ABM one in particular due to impact of high-twist terms and/or error correlations

- Recent CT 10 value is more close to ABM (no SLAC data used, stronger cut on $Q^2$, the error correlations are taken into account)

N.B. The MSTW update gives $0.1155 - 0.1171$ depending on the jet data treatment

Consistent treatment of HT terms in the ABM fit:

- no sensitivity to the low-Q cut

- $\alpha_s(M_Z) = 0.1132(11)$ w/o SLAC and NMC data sensitive to the HT terms → the cross-check with MSTW, CTEQ and NNPDF is highly desirable
Status of QCD theory for jet cross sections

- One-jet inclusive jets hadro-production $P + P(\bar{P}) \rightarrow J(R) + X(s_4)$
  - NLO known since long
  - Large threshold corrections of type $\alpha_s^l [\ln^{2l-1}(s_4/p_T^2)/s_4]_+$ from soft/collinear gluon radiation Kidonakis, Owens, hep-ph/0007268
  - $\ln R$ dependence on jet’s cone size $R$ in small cone approximation de Florian, Vogelsang, arXiv:0704.1677

- Threshold terms (Kidonakis, Owens ’01) used as approximation to unknown NNLO corrections
  - Applied in PDF analyses MSTW, arxiv:0901.0002

- Check of validity of those approximations very important
Theoretical issues in the jet data analysis

- threshold logarithms alone (w/o $\ln R$) at 1-loop fail to describe exact results
  Kumar, Moch, arXiv:1309.5311

- cone size dependence $\ln R$ numerically important
  de Florian, Hinderer, Mukherjee, Ringer, Vogelsang, arXiv:1310.7192

- nice match with exact NNLO (purely gluonic) computation
  Currie, Gehrmann-De Ridder, Glover, Pires, arXiv:1310.3993

Revision of the NNLO PDF analyses based on jet data, particularly using the threshold resummation → impact on the PDF4LHC recommendation
Integral rate of the W/Z production

- Good overall agreement
- The errors in data are bigger than the errors in predictions
- Unmeasured phase space extrapolation?
Impact of the data on PDFs is quite sensitive to the cut on $P_T$ → clarification is necessary