Summary of Structure Functions and PDFs Working Group

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This summary presents personal highlights from the Structure Functions and PDFs Working Group (WG1).

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1. Introduction

The Structure Functions and PDFs Working Group (WG1) consisted of 43 presentations spread over 10 sessions, three of which were held jointly with QCD and Hadronic Final States (WG2), Electroweak Physics and Beyond the Standard Model (WG3), and Future Experiments (WG7). This summary presents personal highlights from these sessions, with the exception of the joint session with WG7 that is presented elsewhere.

2. PDF Fits including HERA combined data

The publication of the HERA combined inclusive data [1] is a legacy document that is at the core of all PDF extractions. A number of groups considered the impact of this data on different PDF sets.

The HERAPDF2.0 set [1], derived only from the HERA data, describes the neutral data well for $Q^2 > 2$ GeV^2 but there are discrepancies at low-x and low-Q^2 (Fig. 1). A possible resolution is provided by the inclusion of higher twist effects. [2, 3]. Another approach using the Bartels-Golec-Kowalski dipole model was shown to describe the HERA data very well, but only if sizeable saturation effects are included [4].
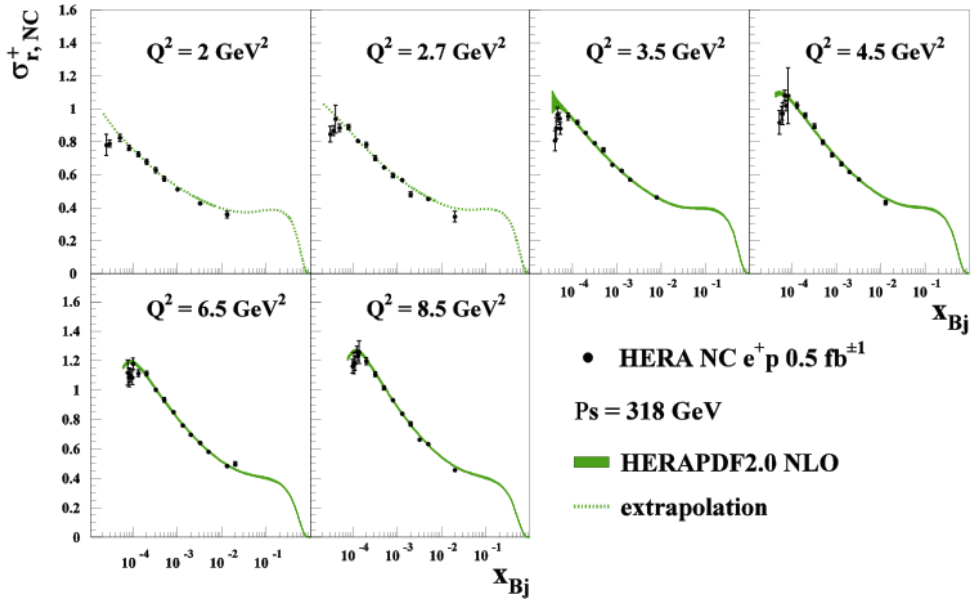

Figure 1: HERA neutral current data with HERAPDF2.0 NNLO fit superimposed [1].

A fit within the MMHT framework [3] was shown to be in good agreement with the MMHT2014 PDFs that used previous HERA cross-section data. There is a very small change in central values and the uncertainties reduce a little – at most by 20% e.g. the cross-section for $gg \rightarrow H$ at 14 TeV changes from $47.69^{+0.63}_{-0.88}$ to $47.75^{+0.59}_{-0.72}$ pb. A comparison with HERAPDF2.0 showed broad agreement but there were some marked differences e.g. in the down valence quark and gluon at high x as shown in Fig. 2.
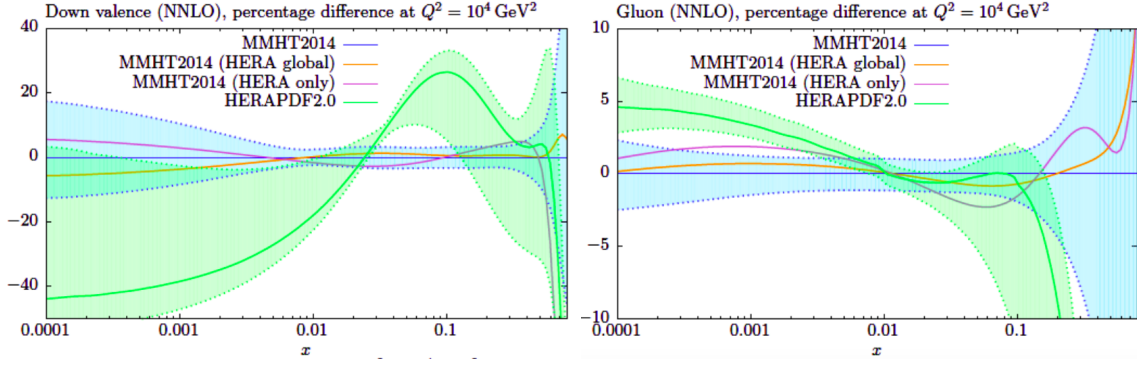
Figure 2: Down valence (left) and gluon PDF (right) compared to MMHT2014 for: a global fit including the new HERA combined data; a fit just using the HERA data; HERAPDF2.0 [3] .

Both MMHT and CT groups find tension between the HERA combined $e^- p$ charged current data and other data sets. In a CT14-like fit [5] a shift in the up quark near $x = 0.3$ is seen if high weight is given to the HERA data (see Fig. 3). It will be interesting to look for this effect in related observables e.g. high rapidity W^+ production at the LHC.
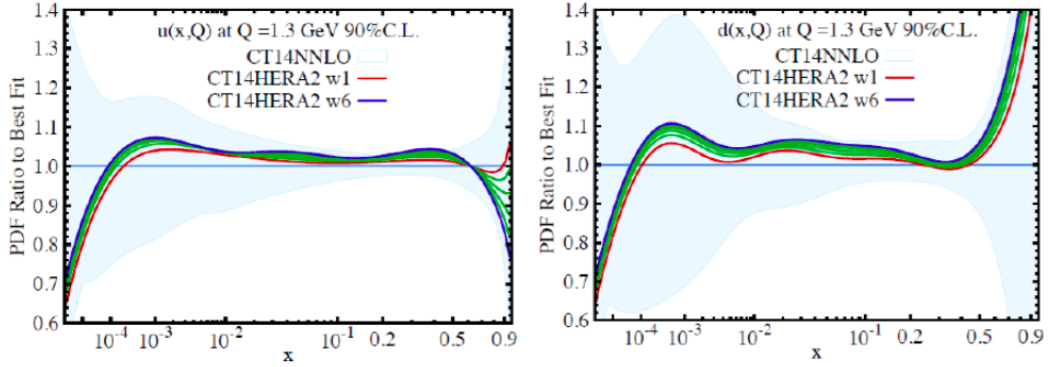

Figure 3: Up and down valence PDF compared to CT14NNLO including HERA data with different weights [5].

3. Analysis and comparison of global PDF sets

There was a lively discussion on how to synthesise the results of the various PDF global fits in order to obtain a theoretical uncertainty on an observable. An extreme example was provided by the $H + t\bar{t}$ production cross-section which changes by 13% depending on which PDF set is used. Various approaches were discussed as expounded in [6] and [7].

There is an open question on the form of $\bar{d} - \bar{u}$ at small x and d/u as $x \to 1$. Strong claims about $\bar{d} - \bar{u}$ at small x being non-zero and d/u as $x \to 1$ being very well constrained (see Fig. 4) were made based on fits [9, 8] including W^+ asymmetry data from $D0$ and W^+, W^- data from LHCb. However, the CJ15 fit [10] includes $D0$ data [11, 12] with a good fit quality (as do CT14,
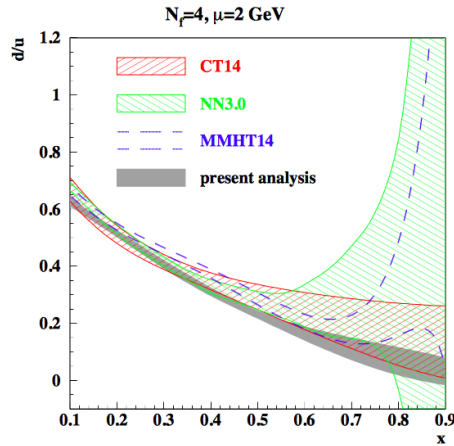
Figure 4: Ratio of down to up valence PDF for various PDF sets. The label 'present analysis' refers to [9].

but with a poorer fit), and see no requirement for any small-x $\bar{d} - \bar{u}$ difference. Similarly, MMHT14 compares very well [13] to data on high rapidity W production at LHCb at 7 TeV [14] and many PDF sets give predictions which compare well to W production at LHCb at 8 TeV [15]. Fits to more precise vector boson data is an obvious area for further study.

A number of talks addressed the flavour decomposition of the proton from another direction. One of the measures of $\bar{d} - \bar{u}$ is the Gottfried Sum Rule. It was described how one can effectively measure free neutron PDFs using the BONUS (Barely Off-shell Neutron Structure) experiment [16], where in electron deuteron scattering one measures the scattered electron in coincidence with a proton tag. This study allows for a re-examination of the Gottfried sum rule from NMC deuteron scattering data [17] down to $x = 0.004$ (relying on an extrapolation at higher Q^2). There is no sign in this of $\bar{d} - \bar{u}$ changing sign or being large at low x. It was also shown how by performing a simultaneous study of precision proton and deuteron data one can fit and also verify predictions for deuteron corrections [10], e.g. D0 W asymmetry data and deuteron DIS probe the down quark for similar x so a simultaneous fit largely determines the deuteron correction.
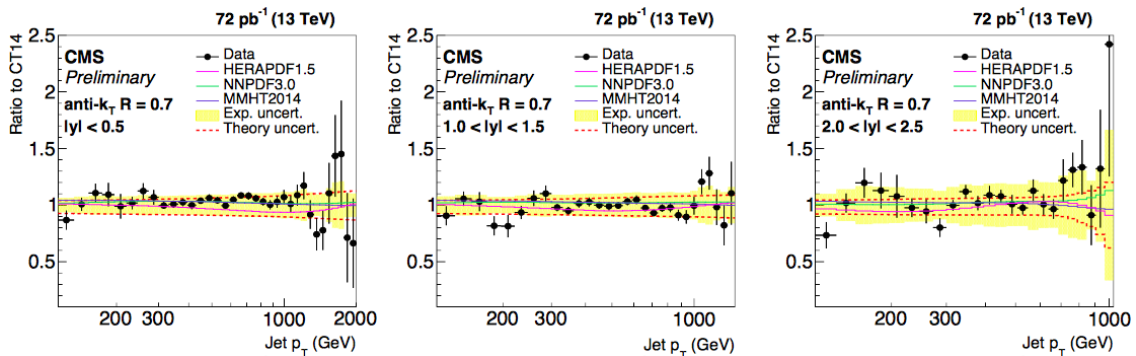

Figure 5: Jet cross-section ratios to ME calculations using CT14 PDFs. The effect of other PDFs is shown by different coloured lines [18].

4. Experimental inputs to PDFs

Several new experimental results that will help to further constrain the PDFs were shown. The CMS collaboration presented inclusive jet cross-sections at 13 TeV [18]. Fig. 5 shows their data compared to CT14 and various other PDF sets. The other end of the energy spectrum was represented by results from H1 [19] who showed inclusive jet cross-sections at low-Q^2, some of which are shown in Fig. 6. The experimental uncertainties are dominated by the jet energy scale and modelling and are significantly smaller than the theory uncertainties, which have large scale uncertainties.
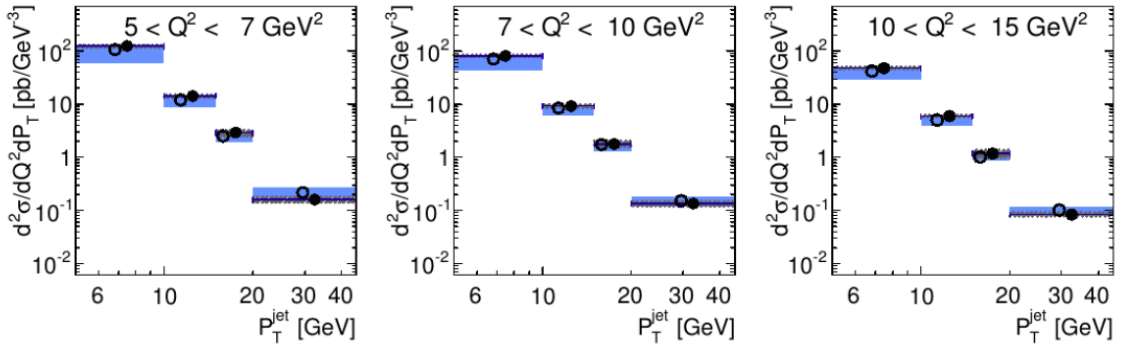

Figure 6: Preliminary results from H1 on inclusive jet cross-section (solid points). The open points are a previous analysis that just used HERA-I data. The coloured band represents the NLO predictions [19].

The ATLAS collaboration presented results on Drell-Yan production including a recent analysis of 8 TeV data [20]. Fig. 7 (left) shows the cross-section for electron-positron pairs with masses between 116 and 1500 GeV, compared to different PDFs. It was demonstrated that these data have sensitivity to the poorly known photons PDFs and can thus be used to constrain them.
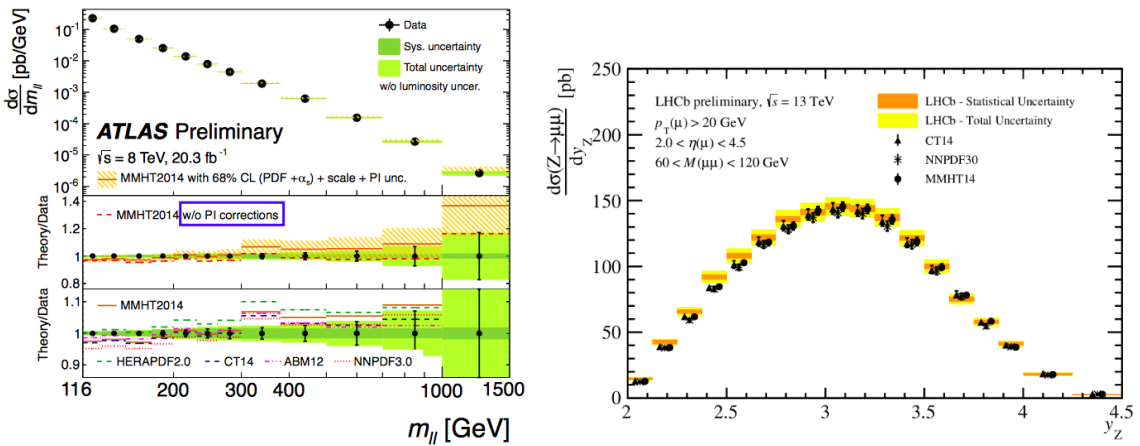

Figure 7: Left: ATLAS results on Drell-Yan production at 8 TeV [21]. Right: LHCb results on Z boson production at 13 TeV [22]. Both are compared to predictions with various PDF sets.

Results on W boson production at 13 TeV were shown by ATLAS [21], while Z boson production at 13 TeV was shown by the ATLAS and LHCb [22] collaborations. Fig. 7 (right) shows the differential cross-section for Z production in the forward region as measured by LHCb, compared to predictions using various PDFs.

5. Nuclear PDFs

There were various presentations of nuclear PDFs in the light of new LHC data. The updated nCTEQ15 PDFs [23] include the impact of some new LHC data on $p - Pb$ scattering via the reweighting technique, but this provides little impact on the PDFs yet. No neutrino data is included in this fit. There was also an update on Kulagin-Petti nuclear PDFs (see e.g. [24, 25]), which model the nuclear corrections rather than primarily fit them to data. This includes account of Fermi motion, off-shell effects, nuclear meson exchange current corrections and contributions from coherent nuclear interactions (nuclear shadowing). So far predictions for LHC $p - Pb$ data appear to be successful. The difference between neutral and charged current nuclear data was investigated for iron targets [26]. As seen in Fig. 8 (left), very good agreement between the two is found at high x, but there is evidence for less suppression in the neutrino nuclear structure functions at low x. There were also a couple of detailed studies in nuclear collisions at the LHC. For example, the centrality dependence of nuclear modifications was investigated [27] by looking at W production as a function of rapidity in three centrality bins, with some evidence for centrality dependence seen. Another topic is the so called neutron skin effect. The neutron distribution is expected to be broader than that of the proton in the nucleus [28], i.e. the neutron tail extends further. This can potentially be seen by looking at the charged hadron ratio in $Pb - Pb$ collisions where deviations from unity are expected with increasing p_T and rapidity. Fig. 8 (right) shows the effect at mid-rapidity: at forward rapidities, deviatinos set in at lower p_T, although the uncertainties are larger.
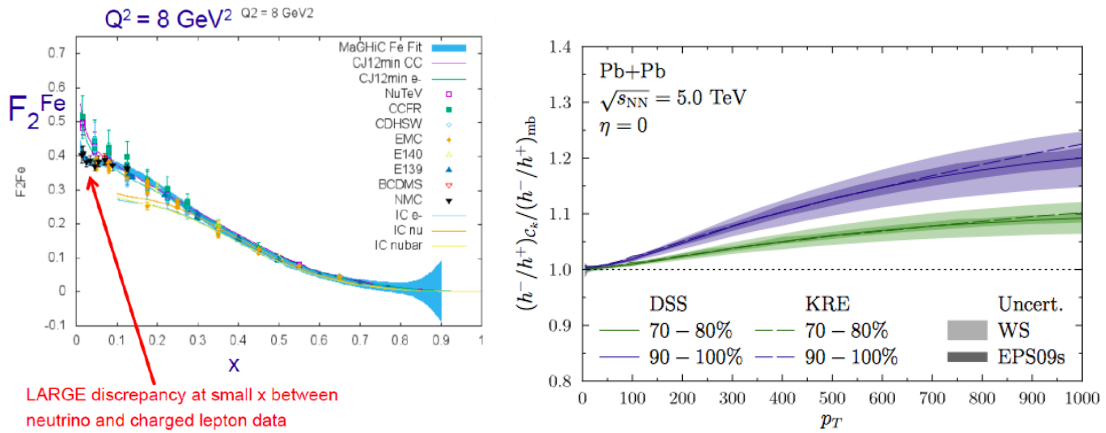
Figure 8: Left: Comparison of F_2^{Fe} measured in neutral and charged current data [26]. Right: Ratio of charged hadrons normalised with minimum bias events for two fragmentation functions. No skin effect corresponds to a value of one [28].

We also saw a presentation of the angular distributions of Drell-Yan dimuons at E906/SeaQuest testing the correlation of the azimuthal and polar angles of leptonic products relative to the initial

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hadronic plane[29], and a study of the ability of pion exchange models to describe both leading neutron electroproduction at HERA and to extract the $\bar{d} \neq \bar{u}$ flavour asymmetry in the proton [30].

6. Transverse Momentum Dependent (TMD) PDFs

The session devoted to TMD PDFs highlighted the importance of including resummations and nonperturbative information, particularly at low k_t , and a proper simulation of parton showers. It included various updates on a new large scale and ambitious project including full coupled quark and gluon evolution using the Monte Carlo approach in a form applicable over all x and Q^2. Results on the fully integrated PDFs obtained in the framework were successfully compared to HERA inclusive cross section data, and updates on the considerable ongoing work for the fully unintegrated PDFs were presented [31]. Saturation effects in the same framework were discussed [32], and TMDlib libraries and a plotter were introduced for the first time [33], also produced by the same group. There was also a contribution studying the role of the nonperturbative input to the (TMD) gluon density in hard processes at the LHC, and deriving the input distribution from a fit of inclusive hadron spectra measured at low transverse momenta in pp collisions at the LHC [34].

7. Theoretical topics

There were a variety of updates on specific theoretical topics relevant for PDF studies. There was a presentation of intrinsic charm based on [35], which looked at the impact on the differential $\gamma + c$ cross section, showing this could be significant. Intrinsic charm was also discussed as part of a NNPDF study [36], where it is determined from a fit to heavy flavour distributions, on top of that generated dynamically from the gluon and light quarks via evolution. The inclusion of EMC data [37] significantly reduces the uncertainties and the fitted charm is lower than purely dynamical charm for $x \sim 0.05$ (see Fig. 9). This has implications for predictions of $W, Z + c$ data at the LHC.
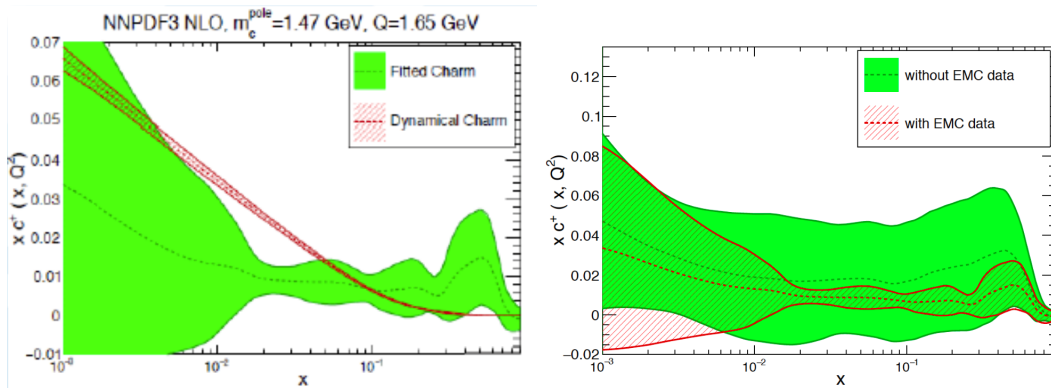

Figure 9: NNPDF fitted charm compared to dynamical charm (left) and to the fit without EMC data (right) [36].

The NNPDF group also presented PDFs with threshold resummations [38], whose effects are much larger at NLO than NNLO, as NNLO already includes much of the effect present at NLO. Data sets for which the threshold corrections are unknown are not used in the fit. The resummed

cross-sections are closer to the fixed order predictions, although the effect at NNLO is arguably no bigger than that due to the missing data.

Another study concentrated on the extreme limits of the PDFs [39], comparing the effectively small-x powers and high-x powers of $(1-x)$ for different PDF sets, finding some significant variation in the latter for the gluon. Improvements to the low-x gluon for NNPDF were shown [40], obtained by incorporating charm production data from LHCb. This allows improved predictions for the prompt atmospheric neutrino flux up to 10^8 GeV, which are consistent with IceCube bounds.

There was an investigation of different methods to incorporate the effect of photons in hard processes [41]. Two different approaches were used for calculating cross sections: either the photon is treated as a collinear parton in the proton, or alternatively the k_T factorization method is used. Also we had a discussion of a method to obtain the double gluon distribution from the single gluon distribution using sum rules [42].

There was s discussion of exclusive J/Ψ and Υ production [43], which in principle can constrain the gluon PDF that is related to generalised parton distributions. The one-loop corrections to the cross section have been calculated but lead to large, opposite sign corrections, particularly for J/Ψ. Theoretical improvements are needed for these processes to be a precision constraint on the gluon distribution.

A procedure for calculating PDFs on the Lattice [44] was presented, using quasi-distributions at finite longitudinal momentum rather than exact distributions in the infinite momentum frame. One can then try to transform the quasi-distributions to the correct limit. Longitudinal momentum $P_3 = 2\pi/L$ on available lattices corresponds to about 0.4 GeV. The values used are hence limited to about 1.6 GeV at best at present, but one can see improvements in results as better lattices are used. We look forward to future developments in this alternative method of PDF determination.

8. Tools for PDFs

There were a number of updates on various tools used to study and present PDFs. APFEL [45] showed a plotting procedure for changing the transition point for heavy flavours in variable flavour schemes, which demonstrates diminished sensitivity to this in PDFs at NNLO compared to NLO. The HERAFitter collaboration, now called XFitter [46], presented theoretical improvements and the inclusion of new data sets. The effect of asymmetric uncertainties was discussed in the CT14 replica PDFs presentation [47], along was the χ^2 distribution of the global fit quality for 1000 CT14 replicas, which use 28 PDF eigenvectors and tolerance ~ 40 for one sigma. Remarkably, this is extremely similar to the equivalent χ^2 distributions for 1000 NNPDF replicas (see e.g. [48]), despite the fact these are obtained from a very different approach. This supports the use of a tolerance criterion in global fits based on the eigenvector approach.

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