Approaching QCD with FCC

a few observations on

QCD
ee pp ep
Jets
Coupling
PDFs
Low x

In memory of Willy van Neerven, Wu-Ki Tung, Guido Altarelli and Lev Lipatov

Max Klein
University of Liverpool, H1 and ATLAS

Talk at the FCC Week 2018, Amsterdam, 11.4.18

Many thanks to Davide D’Enterria, Alain Blondel, Michelangelo Mangano, Voica Radescu + the eh QCD team.
\[ \mathcal{L} = \frac{1}{4g^2} \, G_{\mu\nu}^a \, G_{\mu\nu}^a + \sum_j \bar{q}_j \left( i \gamma^\mu D_\mu + m_j \right) q_j \]

where \( G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + if_{abc} A_\mu^b A_\nu^c \)

and \( D_\mu = \partial_\mu + it^a A_\mu^a \)

That's it!

j ... quark flavors
a,b,c ... 3 colors
\( \mu,\nu \) ... space-time

QCD evolved from a Lagrangian with the property of asymptotic freedom to a sophisticated tool for the calculation of high energy processes. R.K. Ellis Nuovo Cimento 39C(2016)355
The study of the strong interactions was transformed with the advent of accelerators in the multi-GeV energy range. The famous SLAC experiments of the 1960s and 1970s were the first to show the pointlike substructure of hadrons (Bloom et al., 1969; Friedman and Kendall, 1972). The parton model (Feynman 1969; Feynman, 1972; Bjorken and Paschos, 1969) showed that elementary constituents, interacting weakly, could convincingly explain the central experimental results. In the same period, the quark model (Gell-Mann, 1964; Zweig, 1964; Kokkedee, 1969) rationalized hadron spectroscopy. Out of it grew the idea of color (Han and Naumbu, 1965; Greenberg, 1964), a new quantum number postulated in the first instance to avoid the apparent paradox that the quark model seemed to require spin-1/2 quarks with bosonic statistics.

The idea of extending the global color model to a gauge theory (Fritzsch et al., 1973; Gross and Wilczek, 1973b; Weinberg, 1973) was in many ways a natural one, but the motivation for doing so was incalculably strengthened by the newfound ability to quantize gauge theories in a manner that was at once unitary and renormalizable, developed, in large part to describe electroweak interactions. Concurrently, the growth of the technology of the renormalization group and the operator product expansion (Wilson, 1969; Callan, 1970; Symanzik, 1970; Christ, Hasslacher, and Mueller, 1972; Frishman, 1974) made it clear that any field theory of the strong interactions would have to have an energy-dependent coupling strength, to harmonize the low-energy nature of the strong interactions, which gives them their name, with their weakness at high energy (or short distances). The concept of asymptotic freedom (Gross and Wilczek, 1973a; Politzer, 1973), which is satisfied almost uniquely by quantum chromodynamics, brilliantly filled these demands.

Since QCD remains an “unsolved” theory, with no single approximation method applicable to all length scales, the justification for the use of perturbative QCD rests in large part directly on experiment.
The basic experimental set ups:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, .... LHeC)
- 2 hadrons (....SppS, Tevatron, LHC)

Progress in particle physics needs their continuous interplay to take full advantage of their complementarity.

Guido Altarelli DIS2009, Madrid
QCD with ee pp ep

Final state arises completely from short distance interaction of virtual boson with quarks: NO PDFs, but jets, $\alpha_s$.
N jets +0, energy, angles. Unique association of q, g with jets.

Observation of 3-jet events at PETRA to discover the gluon.

S Ellis and D Soper, hep-ph/9306280
Successive combination jet algorithm for hadron collisions.

Many initial partons but only two interact. “rest” is the underlying event of soft i.a.’s.

Dynamical coupling of all components. MPIs.
N jets at large pT +X, pseudorapidity + azimuth.

Ledermann-Drell-Yan scattering, jets.
Scattering depends on parton distributions.
The “Altarelli cocktail” to save the SM (1984, Bern).

“Route royale” to the structure and dynamics of parton interactions inside the proton (nucleon).
Universal partons evolving with resolution scale x BJ fixed through electron kinematics. PDFs + $\alpha_s$.
Redundant e and h final state reconstruction.

Discovery of partons and the QPM … DGLAP.

$\sqrt{s} = 2E_e \approx [G_F V^2]^{-1/2} = 246$ GeV

$\sqrt{s} = 2E_p = 14, 27, 100$ TeV

$\sqrt{s} = 2\sqrt{E_e E_p} = 1.3, 1.8, 3.5$ TeV

ep - “option” which ought to be a real part. Seguil tuo corso, e lascia dir el genti (Dante, KM)
Jets

\[ \frac{d\sigma}{d\Omega} \propto 1 + \alpha \cos^2 \theta + 1 + (0.78 \pm 0.12) \cos^2 \theta. \]

Jets in $e^+e^-$ at $>5$ GeV at SPEAR at Stanford

1. G. Hanson et al., Phys. Rev. Lett. 35, 1609 (1975);

QCD at work at the LHC

1702.05725 Z + n jets ATLAS 3fb$^{-1}$ 13 TeV

100 events with $\geq$ 7 jets

1609.05331 inclusive jets, 26fb$^{-1}$ 8 TeV

10 orders of magnitude in cross section

LHC is the trick to attract a few 1000 physicists to work on QCD: T Sjoestrand, 2007, after we saw ATLAS
pQCD Theory

Substantial and remarkable theoretical progress in pQCD calculations to $N^k$LO, e.g.

* N$^3$LO Corrections to Jet Production in Deep Inelastic Scattering using the Projection-to-Born Method
  
  J. Currie, a T. Gehrmann, b E.W.N. Glover, a A. Huss, c J. Niehues, a A. Vogt d

* QCD calculations for the LHC: status and prospects
  
  Table 1: Methods for the isolation of IR divergent real radiation at NNLO.

<table>
<thead>
<tr>
<th>method</th>
<th>analytic integr. of subtraction terms</th>
<th>type/restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>antenna subtraction [1]</td>
<td>yes</td>
<td>subtraction</td>
</tr>
<tr>
<td>$q_T$-subtraction [2]</td>
<td>yes</td>
<td>slicing; colourless final states</td>
</tr>
<tr>
<td>N-jettiness [3, 4]</td>
<td>yes</td>
<td>slicing</td>
</tr>
<tr>
<td>sector-improved residue subtraction [5–8]</td>
<td>no</td>
<td>subtraction</td>
</tr>
<tr>
<td>nested subtraction [9]</td>
<td>no</td>
<td>subtraction</td>
</tr>
<tr>
<td>colourful subtraction [10, 11]</td>
<td>partly</td>
<td>subtraction; colourless initial states</td>
</tr>
<tr>
<td>projection to Born [12]</td>
<td>yes</td>
<td>subtraction</td>
</tr>
</tbody>
</table>

G Heinrich 1710.04998
QCD & $\gamma\gamma$ physics at FCC-ee

FCC week 2018
Amsterdam, 10th April 2017

David d'Enterria (CERN)


Proceedings, Parton Radiation and Fragmentation from LHC to FCC-ee:
CERN, Geneva, Switzerland, November 22-23, 2016
Feb 4, 2017. 181 pp. COEPP-MN-17-1
Conference: C16-11-21.1 Contributions

Proceedings, High-Precision $\alpha_s$ Measurements from LHC to FCC-ee:
CERN, Geneva, Switzerland, October 2-13, 2015
Conference: C15-10-12.1 Contributions

- FCC-ee $\gamma\gamma$ studies: arXiv:1712.07023 [PHOTON'17 proceeds.]
QCD and $\gamma \gamma$ physics in $e^+e^-$ collisions

- $e^+e^-$ collisions provide an extremely clean environment with fully-controlled initial-state to very precisely probe $q,g$ dynamics:

  Advantages compared to p-p collisions:
  - QED initial-state with known kinematics
  - Controlled QCD radiation (only in final-state)
  - Well-defined heavy-Q, quark, gluon jets
  - Smaller non-pQCD uncertainties:
    no PDFs, no QCD "underlying event", ...

Direct clean parton fragmentation & hadroniz.

- Plus (B)SM physics in $\gamma \gamma$ (EPA) collisions:

hadrons, $X= H, WW, ZZ, \phi,...$
High-precision g-jet studies via $e^+e^-\rightarrow H(gg)+X$

- FCC-ee $H(gg)$ is a "pure gluon" factory:
  - $H\rightarrow gg$ (BR~10% accurately known) provides $O(200,000)$ extra-clean digluon events:
  - High-precision study of gluon radiation & g-jet properties

Handles to split degeneracies

- $H\rightarrow gg$ vs $Z\rightarrow qq$
  - Rely on good $H\rightarrow gg$ vs $H\rightarrow bb$ separation; mandated by Higgs studies requirements anyway?
- $Z\rightarrow bbg$ vs $Z\rightarrow qq(g)$
  - $g$ in one hemisphere recoils against two $b$-jets in other hemisphere: $b$ tagging

Vary jet radius: small-$R \rightarrow$ calo resolution

- $(R \sim 0.1$ also useful for jet substructure)

Vary $E_{CM}$ range: below $m_Z$: radiative events $\rightarrow$ forward boosted

(also useful for FFs & general scaling studies); Scaling is slow, logarithmic $\rightarrow$ large lever arm

- Check $N^\text{LO}$ antenna functions
- Improve $q/g/Q$ discrim.tools (BSM)
- Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
- Colour reconnection? Glueballs?
- Leading $\eta$'s, baryons in $g$ jets?

G. Soyez, K. Hamacher, G. Rauco, S. Tokar, Y. Sakaki

FCC Week, Amsterdam, April 2018

19/23
Physics at a 100 TeV $pp$ collider: Standard Model processes

M.L. Mangano$^{1}$, G. Zanderighi$^{1}$ (conveners), J.A. Aguilar Saavedra$^{2}$, S. Alekhin$^{3,4}$, S. Badger$^{5}$, C.W. Bauer$^{6}$, T. Becher$^{7}$, V. Bertone$^{8}$, M. Bonvini$^{8}$, S. Boselli$^{9}$, E. Bothmann$^{10}$, R. Boughezal$^{11}$, M. Cacciari$^{12,13}$, C.M. Carloni Calame$^{14}$, F. Caola$^{1}$, J. M. Campbell$^{15}$, S. Carrazza$^{1}$, M. Chiesa$^{14}$, L. Cieri$^{16}$, F. Cimaglia$^{17}$, F. Febres Cordero$^{18}$, P. Ferrarese$^{10}$, D. D’Enterria$^{19}$, G. Ferrera$^{17}$, X. Garcia i Tormo$^{7}$, M. V. Garzelli$^{3}$, E. Germann$^{20}$, V. Hirschi$^{21}$, T. Han$^{22}$, H. Ita$^{18}$, B. Jäger$^{23}$, S. Kallweit$^{24}$, A. Karlberg$^{8}$, S. Kuttimalai$^{25}$, F. Krauss$^{25}$, A. J. Larkoski$^{26}$, J. Lindert$^{16}$, G. Luisoni$^{1}$, P. Maierhöfer$^{27}$, O. Mattelaer$^{25}$, H. Martinez$^{9}$, S. Moch$^{3}$, G. Montagna$^{9}$, M. Moretti$^{28}$, P. Nason$^{29}$, O. Nicrosini$^{14}$, C. Oleari$^{29}$, D. Pagani$^{30}$, A. Papaefstathiou$^{1}$, F. Petriello$^{31}$, F. Piccinini$^{14}$, M. Pierini$^{19}$, T. Pierog$^{32}$, S. Pozzorini$^{16}$, E. Re$^{33}$, T. Robens$^{34}$, J. Rojo$^{8}$, R. Ruiz$^{25}$, K. Sakurai$^{25}$, G. P. Salam$^{1}$, L. Salfelder$^{23}$, M. Schönher$^{28}$, M. Schulze$^{1}$, S. Schumann$^{10}$, M. Selvaggi$^{30}$, A. Shivarji$^{14}$, A. Siodmok$^{1,35}$, P. Skands$^{20}$, P. Torrielli$^{36}$, F. Tramontano$^{37}$, I. Tsinikos$^{30}$, B. Tweedie$^{22}$, A. Vicini$^{17}$, S. Westhoff$^{38}$, M. Zaro$^{13}$, D. Zeppenfeld$^{32}$

Abstract

This report summarises the properties of Standard Model processes at the 100 TeV $pp$ collider. We document the production rates and typical distributions for a number of benchmark Standard Model processes, and discuss new dynamical phenomena arising at the highest energies available at this collider. We discuss the intrinsic physics interest in the measurement of these Standard Model processes, as well as their role as backgrounds for New Physics searches.
Physics at a 100 TeV $pp$ collider: Higgs and EW symmetry breaking studies

Editors:
R. Contino$^{1,2}$, D. Curtin$^3$, A. Katz$^{1,4}$, M. L. Mangano$^1$, G. Panico$^5$, M. J. Ramsey-Musolf$^{6,7}$, G. Zanderighi$^1$

Contributors:
C. Anastasiou$^8$, W. Astill$^9$, G. Bambhaniya$^{21}$, J. K. Behr$^{10,11}$, W. Bizon$^9$, P. S. Bhupal Dev$^{12}$, D. Bortoletto$^{10}$, D. Buttazzo$^{22}$, Q.-H. Cao$^{13,14,15}$, F. Caola$^1$, J. Chakrabortty$^{16}$, C.-Y. Chen$^{17,18,19}$, S.-L. Chen$^{15,20}$, D. de Florian$^{23}$, F. Dular$^8$, C. Englert$^{24}$, J. A. Frost$^{10}$, B. Fuks$^{25}$, T. Gherghetta$^{26}$, G. Giudice$^1$, J. Gluza$^{27}$, N. Greiner$^{28}$, H. Gray$^{29}$, N. P. Hartland$^{10}$, V. Hirschi$^{30}$, C. Issever$^{10}$, T. Jeliński$^{27}$, A. Karlberg$^9$, J. H. Kim$^{31,32,33}$, F. Kling$^{34}$, A. Lazopoulos$^8$, S. J. Lee$^{35,36}$, Y. Liu$^{13}$, G. Luisoni$^1$, O. Mattelaer$^{37}$, J. Mazzitelli$^{23,38}$, B. Mistlberger$^1$, P. Monni$^9$, K. Nikolopoulos$^{39}$, R. N. Mohapatra$^3$, A. Papaefstathiou$^1$, M. Perelstein$^{40}$, F. Petriello$^{41}$, T. Plehn$^{42}$, P. Reimitz$^{42}$, J. Ren$^{43}$, J. Rojo$^{10}$, K. Sakurai$^{37}$, T. Schell$^{42}$, F. Sala$^{44}$, M. Selvaggi$^{45}$, H.-S. Shao$^1$, M. Son$^{21}$, M. Spannowsky$^{37}$, T. Srivastava$^{16}$, S.-F. Su$^{34}$, R. Szafron$^{46}$, T. Taii$^{47}$, A. Tesi$^{48}$, A. Thamm$^{49}$, P. Torrielli$^{50}$, F. Tramontano$^{51}$, J. Winter$^{52}$, A. Wulzer$^{53}$, Q.-S. Yan$^{54,55,56}$, W. M. Yao$^{57}$, Y.-C. Zhang$^{58}$, X. Zhao$^{54}$, Z. Zhao$^{54,59}$, Y.-M. Zhong$^{60}$

Abstract
This report summarises the physics opportunities for the study of Higgs bosons and the dynamics of electroweak symmetry breaking at the 100 TeV $pp$ collider.
Double-Higgs Production at FCCpp

<table>
<thead>
<tr>
<th>channel</th>
<th>$\sigma$(100 TeV) (fb)</th>
<th>$N_{30\text{ ab}^{-1}}$(ideal)</th>
<th>$N_{30\text{ ab}^{-1}}$(LHC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hh $\rightarrow (b\bar{b})(W^+W^-) \rightarrow (b\bar{b})(\ell^+\nu_\ell\ell^-\bar{\nu}_\ell)$</td>
<td>27.16</td>
<td>209</td>
<td>199</td>
</tr>
<tr>
<td>hh $\rightarrow (b\bar{b})(\tau^+\tau^-) \rightarrow (b\bar{b})(\ell^+\nu_\ell\bar{\nu}<em>\tau\ell^-\bar{\nu}</em>\ell\nu_\tau)$</td>
<td>14.63</td>
<td>385</td>
<td>243</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow (\ell^+b\nu_\ell)(\ell^-\bar{b}\bar{\nu}_\ell)'$ (cuts as in Eq. 49)</td>
<td>$25.08 \times 10^3$</td>
<td>$343^{+232}_{-94}$</td>
<td>$158^{+153}_{-48}$</td>
</tr>
<tr>
<td>$b\bar{b}Z \rightarrow b\bar{b}(\ell^+\ell^-)$ ($p_{T,b} &gt; 30$ GeV)</td>
<td>$107.36 \times 10^3$</td>
<td>$2580^{+2040}_{-750}$</td>
<td>$4940^{+2250}_{-1130}$</td>
</tr>
<tr>
<td>ZZ $\rightarrow b\bar{b}(\ell^+\ell^-)$</td>
<td>356.0</td>
<td>$\mathcal{O}(1)$</td>
<td>$\mathcal{O}(1)$</td>
</tr>
<tr>
<td>hZ $\rightarrow b\bar{b}(\ell^+\ell^-)$</td>
<td>99.79</td>
<td>498</td>
<td>404</td>
</tr>
<tr>
<td>$b\bar{b}h \rightarrow b\bar{b}(\ell^+\ell^-)$ ($p_{T,b} &gt; 30$ GeV)</td>
<td>26.81</td>
<td>$\mathcal{O}(10)$</td>
<td>$\mathcal{O}(10)$</td>
</tr>
<tr>
<td>$b\bar{b}W^\pm \rightarrow b\bar{b}(\ell^\pm\nu_\ell) + \text{fake } \ell$ ($p_{T,b} &gt; 30$ GeV)</td>
<td>1032.6</td>
<td>$\mathcal{O}(10^{-1})$</td>
<td>$\mathcal{O}(10^{-1})$</td>
</tr>
<tr>
<td>$\ell^+\ell^- + \text{jets} \rightarrow (\ell^+\ell^-) + \text{fake } b\bar{b}$</td>
<td>$2.14 \times 10^3$</td>
<td>$\mathcal{O}(10^{-1})$</td>
<td>$\mathcal{O}(10^{-1})$</td>
</tr>
</tbody>
</table>

Table 35: Signal and background cross sections for the $(b\bar{b})(\ell^+\ell^- + $ $\not{E}_T)$ channel. Due to the limited MonteCarlo statistics, the estimated number of events for the $t\bar{t}$ and $b\bar{b}Z$ backgrounds has a rather limited precision (the 1\(\sigma\) interval is given in the table together with the central value).

Foregrounds: tt, bbZ and HZ: QCD and electroweak theory in new range crucial to control.  
Note: central rapidity for inclusive H production is at x=M/2Ep … low x Bj.

arXiv:1606.09408, p76
Large higher order corrections, sensitive to photon induced processes, large $y, p$ PDF errors
At FCC (LHC), the QCD of the Higgs boson will become an important area of SM research.
High precision requires precise calculations of combined strong+eweight corrections + PDFs
Strong Coupling Constant

\[ \beta(\alpha_s) = - (11 - n_s/3 - 2N_f/3) \alpha_s^2 / 2\pi \]
Recent Articles see: G Dissertori 1506.05407
A Deur, S Brodsky, G de Teramond 1604.08082

\[ \alpha_s(M_Z^2) = 0.1174 \pm 0.0016 \]

w/o lattice 1.5% error

have recently been discussed in quite some detail [84]. In the lattice calculations the role of a measured cross section is taken by suitably defined Euclidean short distance quantities. Lattice calculations have a number of additional, common peculiarities, they need input of the experimental hadronic spectrum and quark masses, they treat only light quarks with perturbative, matching additions of charm and beauty quark effects and they have uncertainties from discretization and truncation of perturbative theory. There follows quite a range in the resulting \( \alpha_s \) values obtained, beyond the simple value of uncertainty quoted, which is achieved by implementing certain quality criteria of the theoretical treatments as are presented in [84].

\(\alpha_s\) via hadronic Z decays

- **Computed at N^3LO:**
  \[ R_Z = \frac{\Gamma(Z \to h)}{\Gamma(Z \to l)} = R_Z^{\text{EW}} N_C (1 + \sum_{n=1}^{4} c_n \left( \frac{\alpha_s}{\pi} \right)^n + O(\alpha_s^5) + \delta_m + \delta_{\text{np}}) \]

- **LEP:** \(\Gamma_Z = 2.4952 \pm 0.0023\) GeV (±0.1%), \(R_\ell^0 = \frac{\Gamma_{\text{had}}}{\Gamma_\ell}, \sigma_{\text{had}}^0 = \frac{12\pi}{m_Z} \Gamma_{\text{had}}, \sigma_{\ell}^0 = \frac{12\pi}{m_Z} \Gamma_\ell^2 \Gamma_Z^2\)

After Higgs discovery, \(\alpha_s\) can be directly determined from full fit of SM:

\[ \Delta \chi^2 \]

\[ \alpha_s(M_Z) = 0.1196 \pm 0.0030\) (±2.5%)

- **FCC-ee:** \(- Z\) stats \((\times 10^5 \text{ LEP})\) will lead to: \(\delta \alpha_s / \alpha_s < 0.2\%\)

- **TH (parametric) uncertainties:** \(\sin^2 \theta_{\text{eff}}, m_W, m_{\text{top}}\)
\( \alpha_s(\mu) \) in Deep Inelastic Scattering

\[ \alpha_s(M_Z^2) = 0.1150 \pm 0.0017 \text{ (exp)} \pm 0.0009 \text{ (model)} \]

H1 inclusive (1998) NLO
hep-ph/0012053 – highest cited H1 only

\[ \alpha_s(M_Z^2) = 0.1157 \pm 0.0020 \text{ (exp)} \pm 0.0029 \text{ (thy)} \]

H1 only jets (2017) NNLO jets!

\[ \alpha_s = 0.1142 \pm 0.0028 \text{ (tot)} \]

H1 inclusive and jets (2017) NNLO

→ It is well possible that \( \alpha_s \) is smaller than hitherto assumed. Current practice to exclude ABM is questionable. Like in the lattice case, one constructs, for perhaps respectable reasons, a norm, which gives the impression of higher accuracy than a critical evaluation would lead to.

Current strong coupling precision at best 1-2%: FCC ee and eh want 1-2 per mille
Higgs Cross Section (LHC)

Figure 18: Higgs production cross-section and 68% C.L. PDF+\(\alpha_s\) uncertainty from the ABM12 fit and from the CT14 set computed at \(\alpha_s = \alpha_s^{ABM}\), normalized by the central value obtained with the PDF4LHC combination.

\[
\sigma = 48.58\text{ pb}^{+2.22}\text{ pb}_{-3.27}\text{ pb}(3.20\%) \text{ (theory) } \pm 1.56\text{ pb}(6.72\%) \text{ (PDF+}\alpha_s) 
\]

C Anastasiou et al, arXiv:1602.00695
\( \alpha_s(\mu) \) at LHeC/FCCeh

<table>
<thead>
<tr>
<th>case</th>
<th>cut ( [Q^2 \ (GeV^2)] )</th>
<th>uncertainty</th>
<th>relative precision (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA only</td>
<td>( Q^2 &gt; 3.5 )</td>
<td>0.00224</td>
<td>1.94</td>
</tr>
<tr>
<td>HERA+jets</td>
<td>( Q^2 &gt; 3.5 )</td>
<td>0.00099</td>
<td>0.82</td>
</tr>
<tr>
<td>LHeC only</td>
<td>( Q^2 &gt; 3.5 )</td>
<td>0.00020</td>
<td>0.17</td>
</tr>
<tr>
<td>LHeC+HERA</td>
<td>( Q^2 &gt; 3.5 )</td>
<td>0.00013</td>
<td>0.11</td>
</tr>
<tr>
<td>LHeC+HERA</td>
<td>( Q^2 &gt; 7.0 )</td>
<td>0.00024</td>
<td>0.20</td>
</tr>
<tr>
<td>LHeC+HERA</td>
<td>( Q^2 &gt; 10. )</td>
<td>0.00030</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 3: Results of NLO QCD fits to HERA data (top, without and with jets) to the simulated LHeC data alone and to their combination, for details of the fit see [5]. The resulting uncertainty includes all the statistical and experimental systematic error sources taking their correlations into account. The LHeC result does not include jet data.

- LHeC/FCCeh lead to 0.1% uncertainty (stat+syst), free of previous DIS deficiencies (HT,nc)
- Joint determination with parton distributions (maybe simplified as H1 published in 2001)
- Needs clarity about low \( x \) behaviour as this uses DGLAP.
- Requires to control heavy flavour (theory) at new level (measure s, c, b, t also)
- Very high precision of NC (\( y \) and Z) and CC and extension to \( x \) near 1 will drastically reduce the PDF parameterisation uncertainties
- Scale uncertainties require that \( N^3LO \) formalism be applied (the bizarre 1/2 .. 2 rule.??)
- The attempt to measure the strong coupling in DIS to permille accuracy requires nothing less than a renaissance of experimental and theoretical DIS (ep) physics
Parton Distribution Functions
The LHeC PDF Programme

Resolve parton structure of the proton completely: $u,v,d,s,?,u,d,s,c,b,t$ and $xg$

Unprecedented range, sub% precision, free of parameterisation assumptions,
Resolve p structure, solve non linear and saturation issues, test QCD, $N^3LO...$
Figure 2: Determination of the valence quark distributions as functions of Bjorken $x$. Plotted are the ratios to the NNPDF result with uncertainties displayed as are provided by the individual sets, left for the up-valence quark and right the down-valence quark distribution. For the LHeC the total uncertainty is plotted and the central value assumed to agree with NNPDF. As non-singlet quantities, the valence quark distributions are approximately the same with varying $Q^2$. 

C Gwenlan, MK
Figure 3: Determination of the gluon momentum distribution in the proton. The expected total experimental uncertainty on $xg$ from the LHeC (dark purple bands) is compared with the most recent global PDF determinations which include the final HERA data, covering for $xg$ a range from $x \sim 5 \times 10^{-4}$ to $x \sim 0.6$, and much of the LHC data from Run I. Left: $xg$ at small $x$; Right at large $x$. 

C Gwenlan, MK
PDFs before HERA - Gluon - $x g(x, Q^2)$
Empowering pp Discoveries

External, reliable input (PDFs, factorisation..) is crucial for range extension + CI interpretation

GLUON

SUSY, RPC, RPV, LQS..

QUARKS

Exotic+ Extra boson searches at high mass

GLUON Pair Production PDF Uncertainty

LHC (14 TeV)

$M_{\tilde{g}} = M_{\tilde{q}}$ [TeV]

$\frac{\sigma}{\sigma_{\text{MSTW08}}}$

CT10

MSTW2008

NNPDF21

HERA10

ABKM09

LHEC

ATLAS today

$W^+$

$\delta$ PDF w.r.t. CT14nlo [GeV]

PDF4LHC15 68% CL

NNPDF 90% CL

NNPDF 68% CL

HERA 68% CL

MMHT14 68% CL

ABM12 68% CL

JR14 68% CL

ATLAS-qqWZ16

CT14nlo 90% CL

$M_{\text{inv}}$ [GeV]
Parton densities extracted from DIS are used to compute hard processes, via the Factorisation Theorem:

$$\sigma(s) = \sum_{A,B} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} p_A(x_1, Q^2) p_B(x_2, Q^2) \hat{\sigma}_{AB}(x_1 x_2 s, Q^2)$$

x times density of parton A

reduced X-section

For example, at hadron colliders

$$V = \gamma^*, W, Z$$

$$X = V, \text{jets}, QQ, H, \text{...}$$

$$Q = b, c, t$$

• Very stringent tests of QCD
• Feedback on constraining parton densities
Strange Strange

Strange quark suppression [dimuons in neutrino data] vs light flavour democracy [W,Z LHC]

\[ R_S = \frac{\langle s + \bar{s} \rangle}{\langle u + \bar{d} \rangle} \]

Also look at MMHT and other results

The strange quark density, after 50 years of DIS, has remained unknown. Is there a valence \( s \)?
Strange Quark Distribution from LHeC

- High luminosity
- High $Q^2$
- Small beam spot
- Modern Silicon
- NO pile-up..

$\rightarrow$ First $(x,Q^2)$ measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4} \ldots 0.1$

$Q^2 = 100 - 10^5 \text{ GeV}^2$

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter
Charm: $F_2^{cc}$ and Mass

Heavy Flavour with LHeC

Beam spot (in $xy$): 7μm
Impact parameter: better than 10μm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, $\varepsilon$, than at HERA
→ Huge improvements predicted

<table>
<thead>
<tr>
<th></th>
<th>HERA</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_c(m_c)/$GeV</td>
<td>1.26</td>
<td>?</td>
</tr>
<tr>
<td>$\delta$(exp)</td>
<td>0.05</td>
<td>0.003</td>
</tr>
<tr>
<td>$\delta$(mod)</td>
<td>0.03</td>
<td>~0.002</td>
</tr>
<tr>
<td>$\delta$(par)</td>
<td>0.02</td>
<td>~0.002</td>
</tr>
<tr>
<td>$\delta(\alpha_s)$</td>
<td>0.02</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Determination of charm mass to 3 MeV:
crucial for $M_W$ in pp or $H \rightarrow cc$ in ep
cf also NNPDF3.1 (arXiv:1706.00428) and refs
Bottom: $F_2^{bb}$ and Mass

Huge improvement vs HERA for the same reasons as for charm
New data H1+ZEUS

Early theory of HQ: J Collins, R.K Ellis: Nucl Phys B360(91)3
E Laenen, S Riemersma, J Smith, W van Neerven NP B392(93)162

Bottom density not well known
Scheme dependence affects LHC interpretations

In MSSM: Higgs from $bb \rightarrow H$ not $gg$
(we only miss the MSSM..)

$m_b(m_b)$ with LHeC to 10 MeV
Nuclear QCD through eA at FCCeh/LHeC

Beauty in Lead

δGluon in Lead

unknown
unknown ← badly known
preliminary

eA: extends kinematic range in $Q^2$, $1/x$ by 3-4 orders of magnitude. Lumi $6 \times 10^{32}$ (J.Jowett)

Measure nPDFs as in ep scattering and determine then the ratio $R(x,Q^2)=nPDF/PDF$


LHeC has been co-initiated and supported by NuPECC

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see: Nestor Armesto FCC week 1/2018, CDR (LHeC) M.K. DOI: 10.1051/epjconf/201611203002
Low x Physics

Rise of Gluon (and Quark) densities towards low x discovered at HERA. This may lead to saturation – non-linear interactions and BFKL ln(1/x) effects. Not discovered at HERA, to much surprise, despite recent ‘speculations’ .. Change of parton distributions + evolution → to be clarified for FCC + (HE) LHC

BFKL papers: *The Pomeranchuk Singularity in QCD/Gauge Theories* 1978/1977
$y=0: \ x = M/2E_p$

Higgs at LHC:
$x_0 = 0.0089$
$x_0 = 0.0013$

Higgs physics is and becomes low $x$ physics
Low x Partons

Low x > 0.01 before HERA

Note: HERA: QCD vacuum dominates p structure at small x. xg vanishes/rises at low/hi Q^2
How to determine **low x evolution** + discover saturation?

How to determine **low x evolution** + discover saturation?

\[
\frac{\partial F_2(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 dz \left[ F_2(\frac{x}{z})P_{qq}(z) + 2 \sum_{i=1}^{N_f} e_i^2 \cdot G(\frac{x}{z})P_{qG}(z) \right]
\]

Needs cleanest DIS constraints, proton, not ion, high E: \( F_2 + F_L \)

High precision \( F_L \) from variation of \( E_e \) independently of LHC/FCC

**LHeC**

High precision \( F_2(x,Q^2) \) from few days of nominal ep running. Needs large \( Q^2 \) and low \( x \sim 1/s \): Impossible at EIC

This constrains DGLAP and rules it out (or not..). cf CDR (LHeC)

LHeC CDR: 1206.2913 J Phys G

\[
F_L(x, Q^2) = \frac{\alpha_s}{\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \frac{4}{3} F_2(z, Q^2) + 2 \sum_{i=1}^{N_f} e_i^2 \cdot G(z, Q^2) \left( 1 - \frac{x}{z} \right) \right]
\]

MK: 1802.04317
\[ L = \frac{1}{4g^2} G_{\mu\nu}^a G^{a\mu\nu} + \sum_j \bar{q}_j \left( i\gamma^\mu D_\mu + m_j \right) q_j \]

where \[ G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + ig^{ab} f_{abc} A_\mu^b A_\nu^c \]

and \[ D_\mu = \partial_\mu + ig t^a A_\mu^a \]

That's it!

\[ j \quad \text{quark flavors} \]
\[ a, b, c \quad \text{3 colors} \]
\[ \mu, \nu \quad \text{space-time} \]

**Developments**

- AdS/CFT
- Instantons
- Odderons
- TOTEM? CERN EP 2017-335
- Non pQCD, Spin
- Quark Gluon Plasma
- QCD of Higgs boson
- $N^k$LO, Monte Carlos...
- Resummation
- Saturation and BFKL
- Photon, Pomeron, n PDFs
- Non-conventional partons (unintegrated, generalised)
- Vector Mesons
- The 3 D view on hadrons..

**Discoveries**

- CP violation in QCD?
- Massless quarks?? Would solve it..
- Electric dipole moment of the neutron?
- Axions, candidates for Dark Matter
- Breaking of Factorisation [ep-pp]
- Free Quarks
- Unconfined Color
- New kind of coloured matter
- Quark substructure
- New symmetry embedding QCD

---

QCD has an exciting future with the FCC
backup
LHC Folklore: PDFs come from pp

LHC data constrain PDFs, BUT do not determine them:

- Needs complete $q_{i\nu}g$ unfolding (miss variety) at all $x$, as there are sum rules
- Needs strong coupling to permille precision, not in pp
- Needs stronger sensitivity (miss $Q^2$ variation) cannot come from $W,Z$ at $Q^2=10^4$ GeV$^2$
- Needs clear theory (hadronisation, one scale)
- Needs heavy flavour s,c,b,t measured and VFNS fixed
- Needs verification of BFKL at low $x$ (only $F_2-F_L$)
- Needs $N^3$LO (as for Higgs)
- Needs external input for pp to find QCD subtleties such as factorisation, resummation...to not go wrong
- Needs external precise input for subtle BSM discoveries
- Needs data which yet (W,Z) will hardly be better
- Needs agreement between the PDFs and $\chi^2+1$ ..

PDFs are not derived from pp scattering. And yet we try, as there is nothing else.., sometimes with interesting results as on the light flavour democracy at $x \sim 0.01$ (nonsuppressed $s/\bar{d}bar$). Can take low pileup runs, mitigate PDF influence .. – but can’t do what is sometimes stated.

**LHeC/FCCeh vs HERA:** Higher $Q^2$: CC; higher $s$: small $x/g$ saturation?; high lumi: $x \to 1$; s, c,b,t.
Final Remark

Testing QCD is in fact more difficult than testing the electroweak sector.


But: it is worth it, possible beyond all expectation in 1983
How could the simple parton picture (with almost non-interacting partons) possibly hold in QCD (—a strongly interacting quantum gauge field theory)?

- **Asymptotic Freedom:**
  A strongly interacting theory at long-distances (even confining) can become weakly interacting at short distances (due to scale dependence implied by the RGE).

- **Infra-red Safety:**
  There are classes of “infra-red safe” (IRS) quantities which are independent of long-distance physics, hence are calculable in PQCD.

- **Factorization:**
  There are an even wider class of physical quantities (inclusive cross sections) which can be factorized into long distance components (not calculable, but universal) & short-distance components (process-dependent, but infra-red safe, hence calculable).
Future Nuclear PDFs with LHeC

From an eA collider one can determine nuclear PDFs in a novel, the classic way. Currently: use some proton PDF base and fit a parameterised shadowing term $R$. Then: use the NC and CC eA cross sections directly and get $R(x,Q^2;p)$ as p/N PDFs.

Gluon density uncertainty in eA

Charm density in nuclei

1 fb$^{-1}$ of sole eA isoscalar data fitted

Impact parameter measurement in eA
FCC-eh PDF program

completely resolve parton structure of proton: u, d, u, d, s, c, b, t and xg
unprecedented kinematic range, sub% precision, free of parameterisation assumptions, N^3LO;
solve non-linear and saturation issues, test QCD, …

today...

FCC parton luminosities (100 TeV)

… then, with FCC-eh

W, Z, VH

H, t, BSM
Are applications of PQCD confined to IRS physical observables?

(Most physical observables are not IRS!)

Fortunately not. In fact, the “QCD Parton Model” for lepton-lepton, lepton-hadron and hadron-hadron scattering cross sections at high energies provides a much more powerful framework for applying PQCD to study a vast range of SM and New Physics processes:

The basic idea behind this class of applications is the factorization of short-distance physics (of leptons, quarks, gluons, new particles) from long-distance physics (of hadrons).
gluon-gluon luminosity uncertainty

quark-quark luminosity uncertainty

arXiv:1607.01831, FCC-pp
gluon at low x

recall – no current data much below $x=5 \times 10^{-5}$ to directly constrain; so even this is an extrapolation for current PDFs at low $x$

**FCC-eh** would provide single, precise and unambiguous dataset (explore low x QCD, DGLAP vs BFKL, non-linear evolution, gluon saturation; implications also for ultra high energy neutrino cross sections)
NNLO singlet splitting functions  A completely analytical result

Moch, Vermaseren, Vogt ’04