Approaching QCD with FCC

Before QCD
Chromodynamics
ee pp ep
Tool for Discovery
High Precision Coupling
Parton Distributions
High Density QCD
Parton Dynamics in Nuclei

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

Max Klein
University of Liverpool, H1 and ATLAS

Talk at the FCC Symposium, CERN, 5.3.2019

Thanks to Nestor Armesto, Davide D’Enterria, Claire Gwenlan, Michelangelo Mangano, Voica Radescu + the eh QCD team.
Two-mile electron linac at SLAC

Pief Panofsky and Burt Richter, 1962

Timeline

- 1963: groundbreaking; construction begins
- 1964: Test Lab building completed
- 1965: Paleoparadoxia discovery
- 1966: first beam in linac, golden bolt ceremony

Graph showing first beam spot profile on May 24, 1966.
Three Messages from the 2m LiNAC

-- you do NOT need to promise to discover dark matter or know what new to expect when you increase the energy range (a comment for Sabine H., we yet may have to readjust our perception about nature, its richness and our ability to predict it. ‘we like to see the field to be driven by experiment’ – Burt Richter 2009)

-- you can build a 2 mile electron linac in 3 years time, if you really want it of course we could build LHeC as a bridge project, if only we decided to do so!

-- electron-proton scattering is the best means to explore the substructure of matter a necessary complement to the LHC/FCC and moreover, now a unique Higgs facility

50 years since the discovery of quarks by the SLAC-MIT ep scattering experiment

W.K.H. PANOFSKY

Vienna 8/1968

Therefore theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon.

SLAC-PUB-502
\[ L = \frac{1}{4g^2} \sum_{\mu} G_{\mu \nu}^a G_{\mu \nu}^a + \sum_j \bar{q}_j (i \gamma^\mu D_{\mu} + m_j) q_j \]

where \[ G_{\mu \nu}^a = \partial_{\mu} A_{\nu}^a - \partial_{\nu} A_{\mu}^a + if_{bc}^a A_{\mu}^b A_{\nu}^c \]

and \[ D_{\mu} = \partial_{\mu} + i t^a A_{\mu}^a \]

That's it!

**QCD**

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

QCD is key for all FCC-ee, eh, hh physics

- Though QCD is *not per se* the main driving force behind FCC, QCD is crucial for many FCC measurements (signals & backgrounds):
  - High-precision $\alpha_s$: Affects SM fits/tests, all hadronic cross sections & decays
  - $N^n$LO+$N^n$LL corrections: Needed for all $x$-sections with initial/final hadrons
  - Heavy-Quark/Quark/Gluon separation, subjet structure, boosted topologies,...: Needed for all precision measurements & BSM searches with jets.
  - High-precision $(n)$PDFs: In h-h collisions, affects all precision $W,Z,H$ (mid-$x$) measurements, all BSM searches (high-$x$), & beyond-DGLAP (low-$x$) studies.
  - Semihard QCD: low-$x$ gluon saturation, multiple hard parton interactions,...

  Note: $Q_0 \sim 10(1)$ GeV at 100 TeV.

- Many-body QCD: Partonic collective behaviour in high particle-density systems, Colour reconnection in "central" h+h collisions; impact on fundamental quantities in jetty final-states ($m_w, m_{top}$ extractions,...),

- Non-pQCD: Control of hadronization+diffraction+... is basic at FCC-pp with $\mathcal{O}(1,000)$ pileup, backgds,...
QCD is far from being fully developed, it will evolve and may break:

### Developments

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

### Discoveries

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

QCD is much more than a tool to find BSM physics, by itself it may lead beyond the SM
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.
QCD with $ee \, pp \, ep$

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

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

\[ V^* \]
\[ \alpha_s(Q^2) \]
\[ N_{\text{jets}}+0, \text{energy, angles. Unique association of } q,g \text{ with jets} \]

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 $p_T +X$, pseudorapidity + azimuth

Ledermann-Drell-Yan scattering, jets
Scattering depends on parton distributions

Saved the SM in 1984, Bern. Discovery of $gg \rightarrow$ Higgs

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

Discovery of partons and the QPM … DGLAP

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

\[ \sqrt{s} = 2E_p = 14, 27, 100 \text{ TeV} \]

\[ \sqrt{s} = 2VE_{eE_p} = 1.3, 1.8, 3.5 \text{ TeV} \]
JETS FROM QUANTUM CHROMODYNAMICS

George Sterman*
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State University of New York at Stony Brook
Stony Brook, New York 11790

and

Steven Weinberg†
Lyman Laboratory of Physics
Harvard University
Cambridge, Massachusetts 02138

HUTP-77/A044
pQCD Theory

Major, impressive 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

1803.09973

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

G Heinrich 1710.04998
QCD at work at the LHC

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

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

100 events with $\geq 7$ jets

10 orders of magnitude in cross section

Multi-jets

Very high scales (low for FCChh..)
HERAPDF2.0 is best and very good while CT14 is worst, as are others. Ideal concept: import PDFs from ep and confront them with LHC data. This tests QCD, avoids PDFs from pp and enables searches for BSM.
Jets

ATLAS: 1706.03192 8 TeV jet data
“Tensions between the data and the theory predictions are observed”

CT14 best, but not good, and HERAPDF2.0 worst, as opposed to W paper

Very extensive studies on data correlations, including also 7 + 13 TeV

NNPDF 1706.00428
Impossible to achieve a good description of all rapidity bins with correlations included…

Used only central bin

There is no simple pattern on how PDF sets describe LHC data. Using their projections as HL-LHC PDFs is indeed questionable.
### 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>$hh \rightarrow (b\bar{b})(\tau^+\tau^-) \rightarrow (b\bar{b})(\ell^+\nu_\ell\bar{\nu}<em>\tau\ell^-\bar{\nu}</em>\tau\nu_\tau)$</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 $(b\bar{b})(\ell^+\ell^- + \ell)$ 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 1σ 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.
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.

$\sigma = 48.58 \, pb^{+2.22 \, pb}_{-3.27 \, pb}^{(+4.56\%)} \, (\text{theory}) \pm 1.56 \, pb^{(3.20\%)} \, (PDF+\alpha_s)$

C Anastasiou et al, arXiv:1602.00695
High-precision g-jet studies via $e^+e^-$→H(gg)+X

- FCC-ee H(gg) is a "pure gluon" factory:
  H→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→gg vs Z→qq

Rely on good H→gg vs H→bb separation; mandated by Higgs studies requirements anyway?
Z→bbg vs Z→qq(g)

g in one hemisphere recoils against two b-jets in other hemisphere: b tagging

Vary jet radius: small-R → calo resolution
(R ~ 0.1 also useful for jet substructure)

Vary $E_{CM}$ range: below $m_Z$: radiative events → forward boosted
(Also useful for FFs & general scaling studies);
Scaling is slow, logarithmic → large lever arm

- Check N$^\circ$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
The strong coupling constant
Recent Articles see: G Dissertori 1506.05407
A Deur, S Brodsky, G de Teramond 1604.08082

\[ \alpha_s(\mu) \]

<table>
<thead>
<tr>
<th>Method</th>
<th>( \alpha_s(M_Z^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice QCD</td>
<td>0.1184 ± 0.0012</td>
</tr>
<tr>
<td>( \tau )-decays</td>
<td>0.1192 ± 0.0018</td>
</tr>
<tr>
<td>DIS</td>
<td>0.1156 ± 0.0021</td>
</tr>
<tr>
<td>Hadron Collider</td>
<td>0.1151 ± 0.0028</td>
</tr>
<tr>
<td>Electroweak Fits</td>
<td>0.1196 ± 0.0030</td>
</tr>
<tr>
<td>( e^+e^- )</td>
<td>0.1169 ± 0.0034</td>
</tr>
</tbody>
</table>

PDG 2016

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

Strong Coupling Constant in $e^+e^-$

From Z pole: dominantly $R_1^0 = \Gamma_{\text{had}} / \Gamma_1$

Error on $R_1^0$ [10^{-5}] today [18]: $\exp$ 25
thy 6

FCCee
exp errors on $R$: stat: 0.06, syst: 0.2-1

Gfitter study: R.Kogler et al.
assumed exp error on $R_1^0 = 1$
thy = thy(18)/4 *)

Error on strong coupling FCC-ee
with present thy uncertainty ± 0.92%
no theory uncertainty 0.17%
¼ of present theory uncertainty 0.25%

1809.01830 *) Theory Workshop on Tera-Z 1/18

Updated electroweak fit: [1803.01853] $\alpha_s(M_Z^2)$

+ other determinations: WW, jet rates event shapes: criterion is precision.

In order to meet the experimental precision of the FCC-ee Tera-Z for ElectroWeak Pseudo-Observables (EWPOs), even 3-loop calculations of the $Z f \bar{f}$-vertex will be needed, comprising the loop orders $O(\alpha \alpha_s^2), O(N_f \alpha^2 \alpha_s), O(N_f^2 \alpha^3)$ and corresponding QCD 4-loop terms. This is a key problem and discussed in Chapters B and D.

A. Blonde11, J. Gluza*2, S. Jadach3, P. Janot4, T. Riemann2,5 (editors),
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 (γ 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
Jet cross sections sensitive to $p_{T,\text{min}}$ of $\sim 20$ TeV. Departures in the cross section from 4 or 8 TeV gluinos present in the evolution of the strong coupling at high scales. Study (right) as functions of statistical and systematic error. Precision inferior to eh/ee.
Electroweak + QCD in ep

Very high cross sections extending hugely beyond electroweak scale. Large luminosity and high precision in ep enable stringent tests of electroweak physics in spacelike region.

Determination of the weak NC light quark couplings.
Running of $\sin^2 \Theta_W$ up to 2 TeV [from 0.1 GeV with PERLE]
10 MeV precision on $W,Z$ mass
CKM as $V_{tb}$, $V_{cs}$ very precise
Not limited by PDFs

At FCC(ee/eh/hh) the combined QCD+eweak corrections will become mandatory to control.
Parton Distribution Functions
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 $s/d_{\bar{b}}$).

**LHeC/FCCeh vs HERA:** Full resolution of parton contents for $x$ between $10^{-6/7}$ and 1
Strange quark suppression [dimuons in neutrino data] vs light flavour democracy [W,Z LHC]

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

\[ R_s = \frac{s + \bar{s}}{u + \bar{d}} \]

NNPDF3.1 arXiv:1706.00428, note:
“xFITTER16” = ATLAS: 1612.0301
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

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter
50 years after the discovery of quarks we still do not know the d/u limit for $x \to 1$
Prospects FCCh: Sea Quarks

Ubar distribution at $Q^2 = 1.9 \text{ GeV}^2$

Dbar distribution at $Q^2 = 1.9 \text{ GeV}^2$

Note this may be obtained from a year of operation (FCCep or LHeC) – study forthcoming
Prospects FCCeh: Gluon Distribution

Gluon Distribution

Gluon distribution at $Q^2 = 1.9 \text{ GeV}^2$

Small $x$: FCC-ep reaches UHE neutrino range

Large $x$: inclusive and jets (to come)
Charm, beauty and sensitive also to the top fraction of proton momentum: 6 flavour scheme
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>$m_c(m_c)/\text{GeV}$</td>
<td>1.26</td>
<td>?</td>
</tr>
<tr>
<td>$\delta(\text{exp})$</td>
<td>0.05</td>
<td>0.003</td>
</tr>
<tr>
<td>$\delta(\text{mod})$</td>
<td>0.03</td>
<td>~0.002</td>
</tr>
<tr>
<td>$\delta(\text{par})$</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
Physics at Small $x$
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 $\rightarrow$ to be clarified for FCC + (HE) LHC
How to determine **low x evolution** + discover **saturation**?

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

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 \( y \) and low \( x \sim 1/s \): Impossible at EIC

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

MK: 1802.04317
Discovery of BFKL in ep through $F_2$ and $F_L$

High precision measurements of $F_2$ and $F_L$ at small $x \sim 1/s$ to discover new parton dynamics, discussed in detail in 1802.04317 MK

NNPDF study 1710.05935 + FCC book
Good collaboration with all PDF fit groups
New QCD Physics at Small $x$ in $ep$

**Elastic J/Psi production**

\[ \gamma^* + p \rightarrow J/\psi + p \]

- $Q = 0, W_{TP} = 2.5$ TeV

**Diffraction**

- ZEUS-SJ
- $E_p = 7$
- $E_p = 50$
- $\mu^2 = 6$ GeV$^2$

**Diffractive gluon density**

t distribution related to Fourier transform of scattering amplitude in impact parameter space

N. Armesto et al: 1901.09076
Electron-Ion Scattering at High Energies
Electron-Ion Scattering at High Energies

Need high energies to match the QGM scales, to exploit weak interactions and to reach very low Bjorken $x$. **CERN and Europe have a unique EIC scattering programme and should exploit that.** Studied as part of the LHeC CDR and for FCCeh.

**Goal:** QCD of Nuclei, Confinement, Nuclear effects vs non-linear i.a.s, Base of QGP..

Extension of kinematic range by 4 orders of magnitude promises revolutionary changes
What we can learn in an \textit{ep/eA} collider

We do not have a \textbf{QUANTITATIVE} understanding of the nuclear behaviour

The colliding objects \hspace{1cm} Early stages \hspace{1cm} Analyzing the medium

\begin{itemize}
  \item Gluons from saturated nuclei
  \item \textit{Gluon Saturation}
  \item \textit{QCDeps}?
  \item \textit{QGP}?
  \item \textit{Reconfinement}?
\end{itemize}

\begin{itemize}
  \item Probing the medium through energetic particles:
    \begin{itemize}
      \item Dynamical mechanisms for opacity
      \item How to extract accurately medium parameters?
    \end{itemize}
\end{itemize}

\begin{itemize}
  \item Dense regime: lack of information about
    \begin{itemize}
      \item small-\textit{x} partons
      \item correlations
      \item transverse structure
    \end{itemize}
\end{itemize}

\begin{itemize}
  \item Particle production at the very beginning:
    \begin{itemize}
      \item Which factorization?
      \item How can a system behave as isotropised so fast?
    \end{itemize}
\end{itemize}

\begin{itemize}
  \item \textit{ep} and \textit{eA}:
    \begin{itemize}
      \item nuclear \textit{WF} & \textit{PDFs}
      \item mechanism of particle production
      \item tomography
    \end{itemize}
\end{itemize}

\begin{itemize}
  \item \textit{ep} and \textit{eA}:
    \begin{itemize}
      \item initial conditions for plasma formation
      \item how small can a system be and still show collectivity?
    \end{itemize}
\end{itemize}

\begin{itemize}
  \item \textit{ep} and \textit{eA}:
    \begin{itemize}
      \item modification of radiation and hadronization in the nuclear medium
      \item initial effects on hard probes
    \end{itemize}
\end{itemize}
DIS ePb: simulated data from LHeC/FCCeh

Huge extension of range. For DIS: 3-4 orders of magnitude

Full systematic errors considered

Very precise: kinematics from scattered lepton and hadronic final state.

Neutral Current down to $x=10^{-5/6}$
- charm and beauty from ePb

Precise Charged Currents in eA
- flavour decomposition
- strange density (Ws → c)

Coherent, precise determination of quark and gluon PDFs for protons and nucleus
Determination of $p$ and $A$ PDFs at LHeC/FCCeh

Region of no DIS data $\leftrightarrow$

current status $\rightarrow$ on $xg \text{ Pb} / \text{p}$

N Armesto, FCC Physics Week 1/2018
Summary

QCD in hh: a tool to understand the observations. Tests at unprecedented scales. Through LHC QCD got a major boost (theory and phenomenology)

QCD in ee: strong coupling, perturbative parton radiation [jet substructure, fragmentation..] non-perturbative parton radiation[colour reconnection, hadronisation..].

QCD in ep: strong coupling to per mille, complete resolution of partonic proton contents [also n,y,IP and 3D] discovery of non-linear gg interactions, N^3LO prediction of H

QCD in eA: establish quantitative understanding of parton interactions in nuclei for the first time. Disentangle nuclear from non-linear effects. The QGP in QCD

QCD in AA: cf Liliana Apolinario later today.

Huge steps from LHC to FCC-hh, from LEP to FCC-ee and from HERA to LHeC/FCCeh. QCD physics at the FCC is a guaranteed and fundamental physics programme which will support, and on its own lead to, discoveries. QCD remains a most fascinating part of particle physics (related to H, eweak, BSM) and is still far from being ‘done’.
backup
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.
Direct Photons

1612.04333  direct \gamma at NNLO
\( \alpha_s(\mu) \) 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

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

H1 only jets (2017) NNLO jets!

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

H1 inclusive and jets (2017) NNLO

\( \rightarrow \) 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