CERN, Workshop on the LHeC, 24 June '15

Importance of Deep inelastic scattering in the 21st century

Guido Altarelli

Universita' di Roma Tre
and CERN

Following the comprehensive & quantitative physics case for the LHeC presented by Monica D'Onofrio here I will only add a number of general comments

In spite of the large effort in theory and experiment over ~50 years still our knowledge of DIS is in many respects surprisingly not satisfactory

Some examples:

- Ambiguities on the pdf's
- The determination of α_s from DIS
- Only recently some data on F_L, F_{charm}, F_{bottom} have been obtained at HERA
- • • • •

The physics motivation for the LHeC is tightly related to the future continuation of the hadron collider experiments, e.g. HL-LHC, FCC(100 TeV)

While the LHeC is not a main discovery machine
[in this respect no competition with the e+e- or hadron colliders]
indeed the LHeC would considerably sharpen
the hadron collider potential in terms of theoretical control and precision

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indeed the LHeC would considerably sharpen
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Of course I am talking from a purely scientific point of view, not a financial one: may be there will be no available resources. This would imply a big damage

The eP option was present since the beginning of the LHC as a natural complement to the pp main programme

ECFA-CERN Workshop
Large Hadron Collider in the LEP Tunnel
Lausanne March '84

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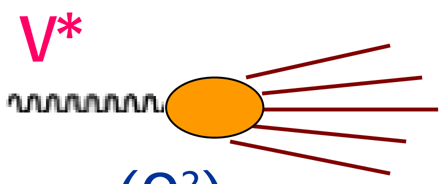
PHYSICS OF ep COLLISIONS IN THE TeV ENERGY RANGE

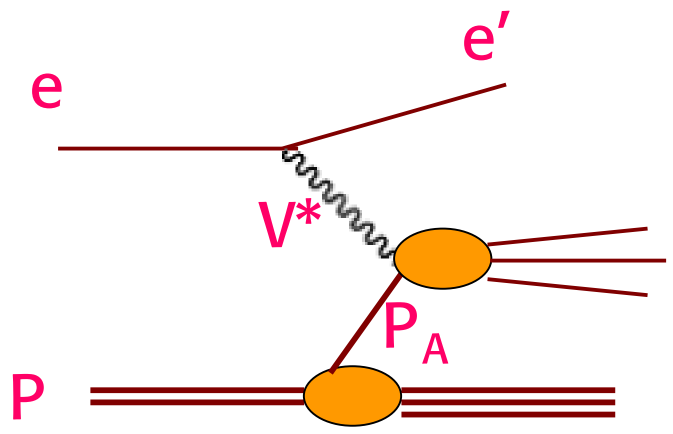
G. Altarelli*), B. Mele*) and R. Rückl,
CERN, Geneva, Switzerland
(Presented by G. Altarelli)

ABSTRACT

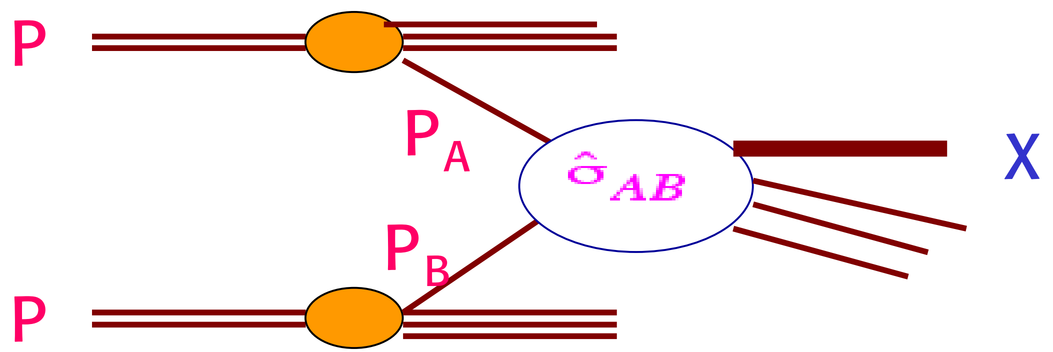
We study the physics of electron-proton collisions in the range of centre-of-mass energies between $\sqrt{s} \simeq 0.3$ TeV (HERA) and $\sqrt{s} \simeq (1-2)$ TeV. The latter energies would be achieved if the electron or positron beam of LEP [$E_e \simeq (50-100)$ GeV] is made to collide with the proton beam of LHC [$E_p \simeq (5-10)$ TeV].



$\alpha_s(Q^2)$



$\alpha_s(Q^2)$ & $q(x,Q^2)$, $g(x,Q^2)$



The basic experimental set ups for accelerator particle physics:

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

The pdf are defined in DIS

The theory of inclusive DIS is crystal clear

Thru the factorization "theorem" the pdf's and α_s determine the hadron collider rates

At present proton pdf uncertainties dominate the theory errors on crucial processes, including Higgs production

The LHeC would allow the separate precise extraction of the pdf's of all flavours and also an improved, solid measure of the QCD coupling.

The pdf will be measured down to very small x (~ 10^{-5}; no data today below 10^{-4})
Precision will be increased at medium x (advantage for Higgs production)
Great improvement at large x (poorly constrained till now)

We often hear the statement that all the relevant info on pdf's can directly be obtained from the LHC without need of the LHeC

Not really true. Certainly not at the same level of precision
One example:

The factorization "theorem" is essential.
Not fully proved theoretically (beware of non pert. effects)
[nearly complete arguments only for Drell-Yan & similar]
Should finally be experimentally tested with precision

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

x times density of parton A

reduced X-section

One way: precisely measure gluons and quarks at large x in DIS, evolve in Q^2, and predict the jet rates at large p_T at the LHC

The measurement of α_s is another issue where DIS is essential

Hadron collider processes most often start with powers of α_s: for example the Higgs g-g crossection starts with α_s^2.

The existing averages of α_s measurements are based on a list of different sources, typically computed at NNLO or even beyond.

However for some entries the stated error is taken directly from the original works and is not transparent from the outside (a typical example is the lattice determination).

In my opinion one should select few theoretically simplest and cleanest processes for measuring α_s

Note that this is what is done in QED where α is measured from one single very precise and theoretically reliable observable (one possible calibration process is at present the electron g-2)

The cleanest processes for measuring α_s are the totally inclusive ones (no hadronic corrections) with light cone dominance, like e+e- annihilation or Z decay, scaling violations in DIS and perhaps τ decay

(but, for τ decay the energy scale is dangerously low).

One should extract α_s from these cleanest methods and consider all other ways as tests of the QCD theory.

The very clean theoretical environment largely compensates for the limited sensitivity

$$R_{e+e-, Z, \tau} \sim R^0_{e+e-, Z, \tau} [1 + o(\alpha_s)]$$

scaling violations in DIS (small log effects):

$$dF/d\log Q^2 \sim \alpha_s\, q \text{ and/or } \alpha_s\, g$$

correlation α_s <---> pdf's

The situation of measuring α_s from DIS is at present not really satisfactory in terms of precision.
Different analysis with different input and assumptions lead to different values

Examples of NNLO analysis

$$\alpha_s(m_Z) = 0.1134 \pm 0.0011 \text{ (exp)}+?$$

Alekhin, Blumlein, Moch '12

$$\alpha_s(m_Z) = 0.1158 \pm 0.0035 \text{ (exp)}+?$$

Jimenez-Delgado, Reya '09

Differ by pdf parametrizations, g at large x, set of data

From combined H1+ZEUS data

$$\alpha_s(m_Z) = 0.1147 \pm 0.0012 \text{ (exp)}+?$$

Alekhin, Blumlein, Moch '10

Global fit to α_s and PDF dominated by DIS but not only DIS

$\alpha_s(m_Z) = 0.1171 \pm 0.0014(\mathrm{exp}) + ?$ (NNLO)

Martin, Stirling, Thorne, Watt '09

MRST attribute their larger value of α_s to a more flexible parametrisation of the gluon and claim that the Tevatron jets are needed to fix g at large x

The Neural Network approach suppresses g parametrization errors (The NNPDF Coll. '11)

DIS only $\alpha_s(m_Z)=0.1166\pm0.0008(\mathrm{exp}) + 0.0009\ (\mathrm{th})$ (NNLO)

Including Tevatron jets may be important to constrain g at large x (and then, via momentum conservation, also at small x). But jets rates only known at NLO accuracy

$\oplus$ With jets and DY $\alpha_s(m_Z)=0.1173\pm0.0007(\mathrm{exp}) + 0.0009\ (\mathrm{th})$

We have seen that the situation of measuring α_s from DIS is at present not really satisfactory in terms of precision. Different analysis with different input and assumptions lead to different values

This is due in part to the correlation between the extracted value of α_s and the behaviour of the gluon at large x (often borrowed from jets at large p_T, assuming factorization)

Also, some other input external to DIS, for example from Drell-Yan processes, is still needed to disintangle the different quark flavor contributions.

Clearly the LHeC could much improve the measurement of α_s from DIS

Summary

Ref.: G.A. ArXiv: 1303.6065

- Z inclusive decay and EW precision tests:

  $\alpha_s(m_Z) = 0.1190 \pm 0.0026$

- DIS eP: $\alpha_s(m_Z) = 0.1165 \pm 0.0020$ ← A low central value? Different groups, different data, different results
- τ inclusive decay: $\alpha_s(m_Z) = 0.1194 \pm 0.0021$

Average from Z and DIS only: $\alpha_s(m_Z) = 0.1174 \pm 0.0016$

also adding τ inclusive decay: $\alpha_s(m_Z) = 0.1184 \pm 0.0011$

Note: the PDG '14 average is: $\alpha_s(m_Z) = 0.1185 \pm 0.0006$

dominated by lattice

without lattice : $\alpha_s(m_Z) = 0.1183 \pm 0.0012$

α_s Snowmass13 report – arXiv:1310.5189

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

LHeC beyond pdf's and α_s

- Extended QCD probes & tests
- eA Collisions
- BSM

Not the main motivation but still a very wide and interesting programme

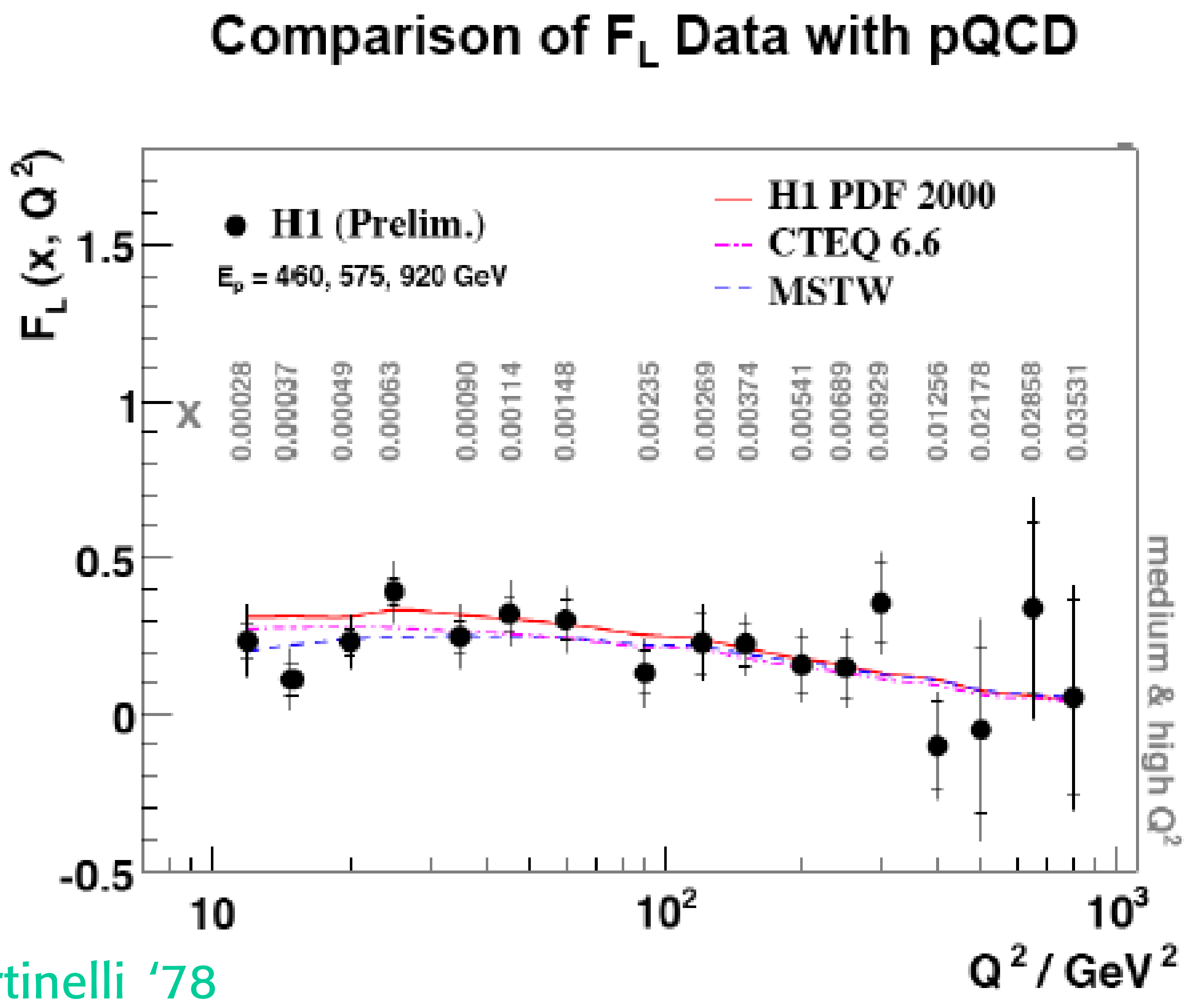
A very attractive byproduct of the LHeC would be a whole chapter of QCD studies in domains that could not so far be studied in sufficient depth or were largely inconclusive

Examples:

- The longitudinal structure function
- Structure functions at small x: leading twist (BFKL....)
- Structure functions at small x: saturation, multipartons

  clarifying the small-x domain
  disentangling resummation effects
  approaching the saturation regime
- Diffractive DIS, Pomeron structure function
- Non forward Compton and generalized pdf's
- • • •

A fundamental QCD prediction still awaiting for a precise test



Altarelli, Martinelli '78

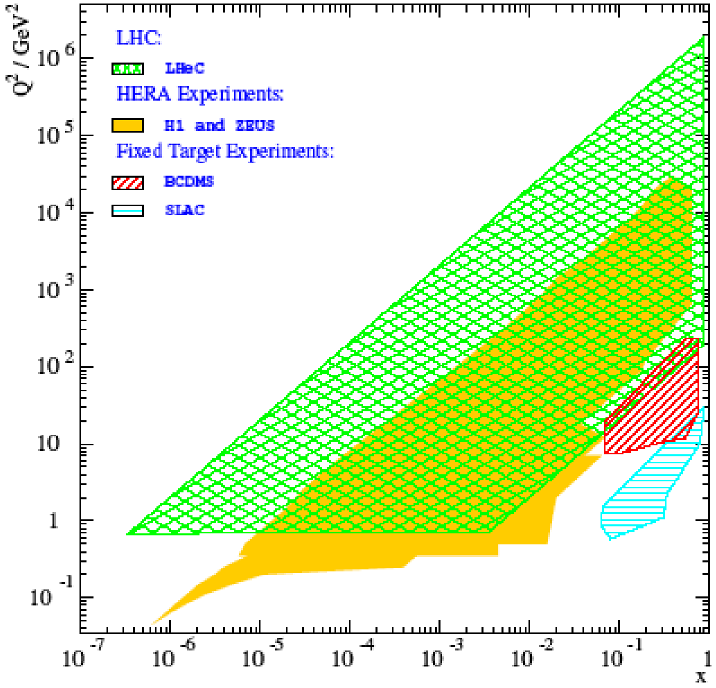
$$F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} x^2 \int_x^1 \frac{dy}{y^3} \left[\frac{8}{3} F_2(y,Q^2) + \frac{40}{9} yg(y,Q^2)(1-\frac{x}{y}) \right]_{n_f=4}$$

Structure functions at small x

At fixed Q^2, also considering the larger luminosity, LHeC can go more than 2 orders of magnitude lower in x than HERA.

This is an interesting perspective both for ep and eA

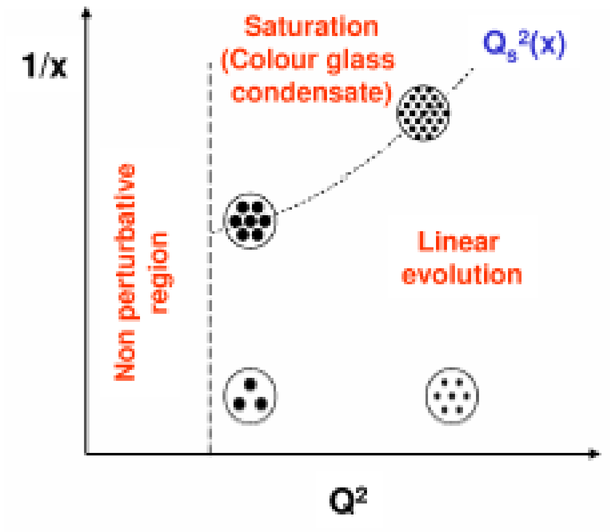
In ep, contrary to some occasional statements, there is no compelling evidence for deviations from leading twist perturbative (but resummed) evolution (no saturation, no parton recombination....).



The region where we expect the leading twist perturbative regime to fail is at very small x where the singlet splitting functions finally take off

This is at the boundary of the LHeC domain

Saturation: when in a sphere of r=o(1/Q) there are too many gluons (large Q, small x) --> colour glass condensate



At the LHeC one goes deeper in the small-x region and it should be possible to test the details of the resummed evolution and of the transition region

- The ion beam will enhance the potentialities for saturation eA

- Parton densities in the nucleus
- Factorization in eA, AA
- QCD radiation and hadronization in the medium
- • • •

Important for achieving the goals of $e^{\pm}$-ion collisions

BSM Complementing the LHC on new physics

- Higgs WWH, ZZH, Hbbbar .... couplings
- Anomalous Wtb or Zttbar couplings
- Electroweak precision tests
- Contact eeqq interactions
- Leptoquarks
- R-parity violating SUSY
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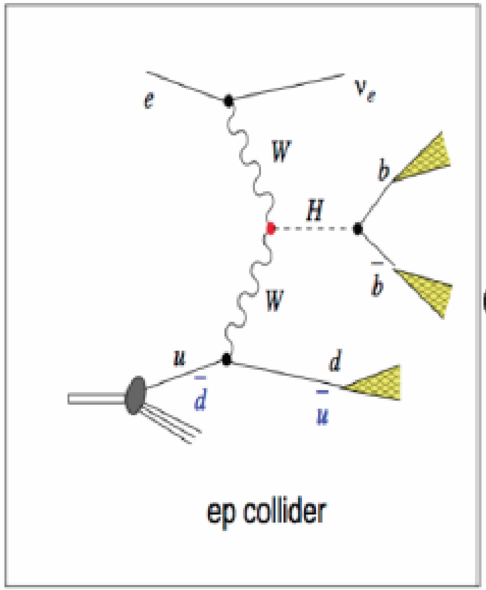
Difficult to go beyond the LHC limits (those in 10 years)

Higgs production

Cannot change the whole picture
but certainly an important
complementary information

ep



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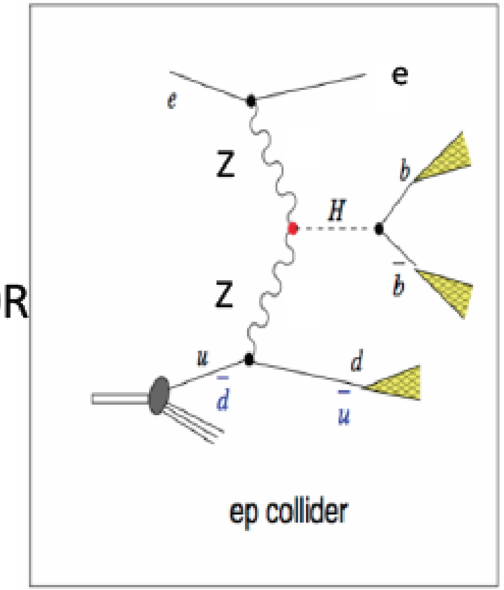
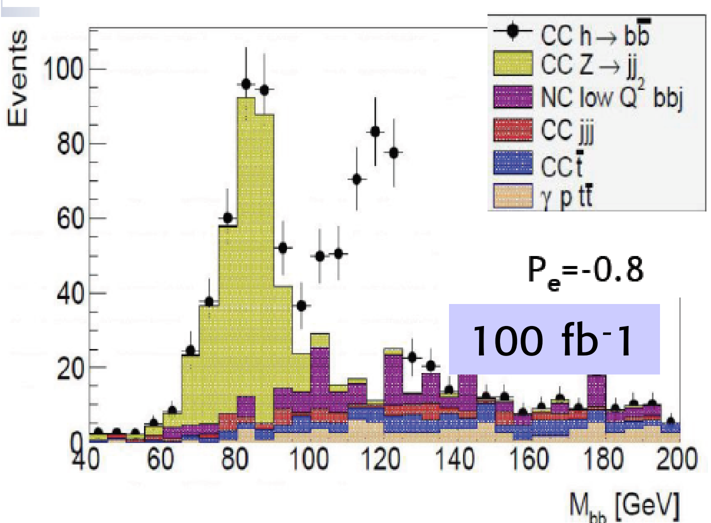


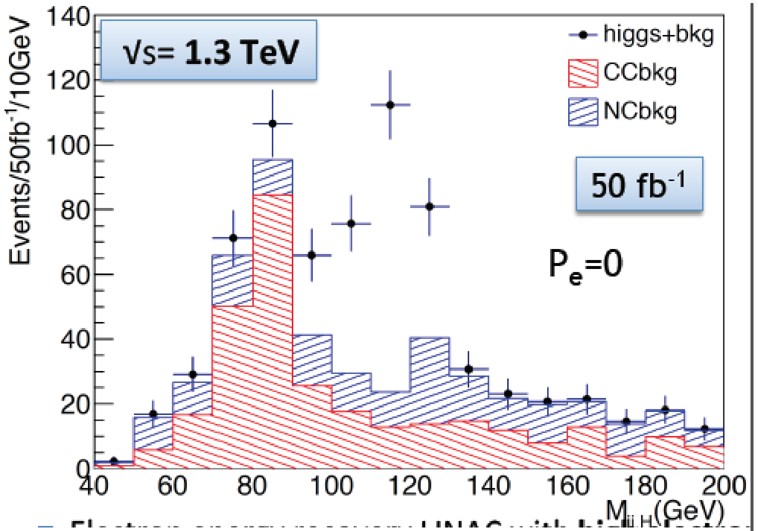
- Higgs production in ep comes uniquely from either CC or NC
  - Pile-up in e-p at 10^{34} = 0.1
  - Clean(er) bb final state, S/B ~ 1

→ Clean, precise reconstruction and easy distinction of WWZ and WWH

D'Onofrio



Include also photo-production background



Conclusion

A large number of open questions remain in the domain of DIS

It would be a waste not to exploit the 7 TeV beams for ep and eA physics at some stage during the LHC time

It is difficult to deny that the LHeC results would much improve the future hadron collider expectations in terms of theoretical control and of precision

The physics programme of the LHeC is wide and interesting in itself, although not directly directed towards the most crucial issues of particle physics today