ICHEP2012 Melbourne

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Partons, QCD and Low x Physics at the LHeC

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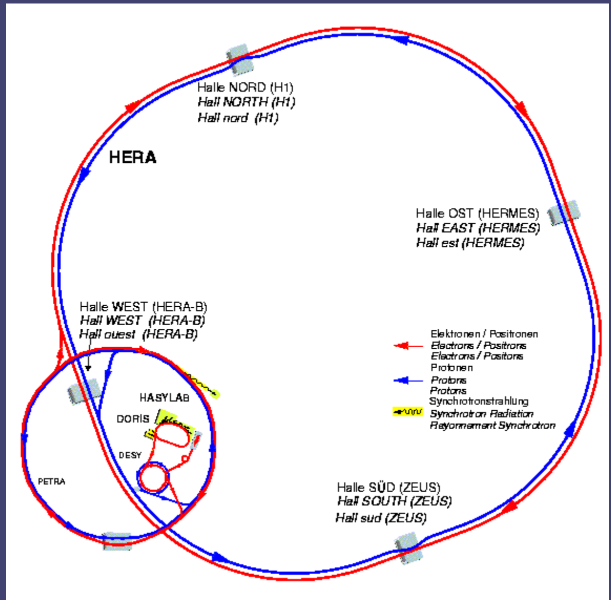
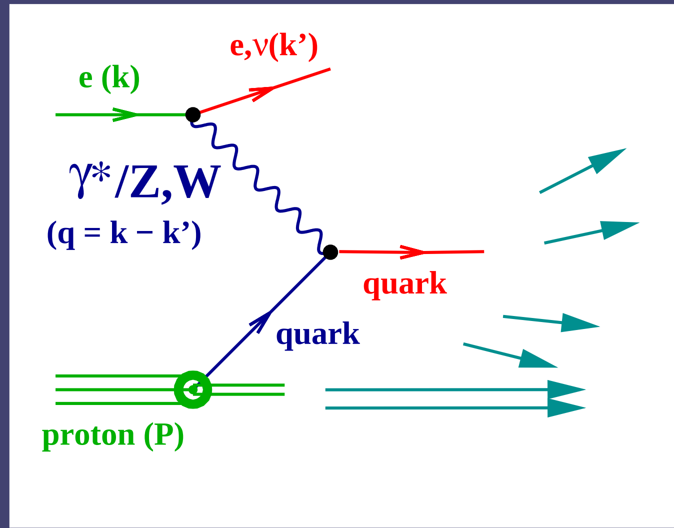
The LHeC Study Group
http://cern.ch/lhec

ep colliders: HERA

The (only) ep HERA collider: QCD-precision machine using DIS processes



$E_p = 0.92$ TeV
$E_e = 27.5$ GeV
$\sqrt{s} = 0.318$ TeV
$0 \lesssim Q^2 < 10^5$ GeV^2

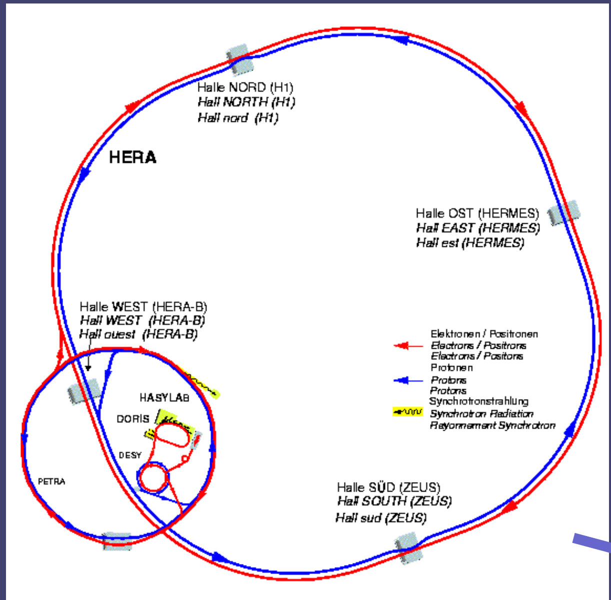


- Many high-precision results (data taking: 1992-2007):
  - proton structure and PDFs
  - α_s, tests of QCD and EW sector
  - new particles/interactions
  - jet production
  - photon structure
  - heavy flavours
  - diffraction ...

Still many issues unresolved ...

ep colliders: HERA $\longrightarrow$ LHeC

The (only) ep HERA collider: QCD-precision machine using DIS processes



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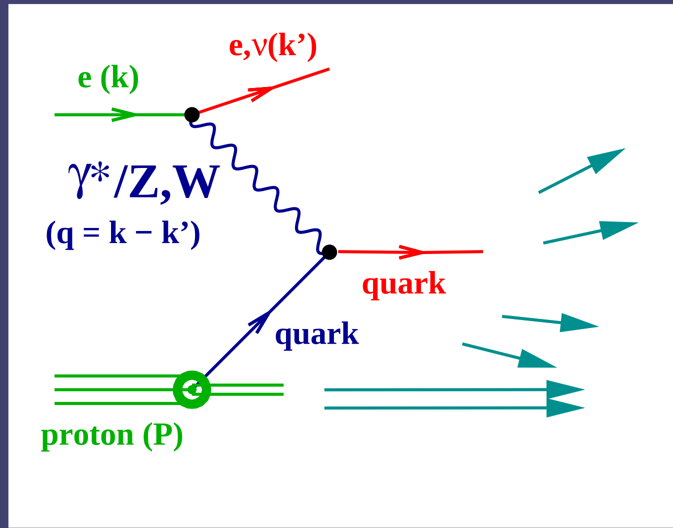
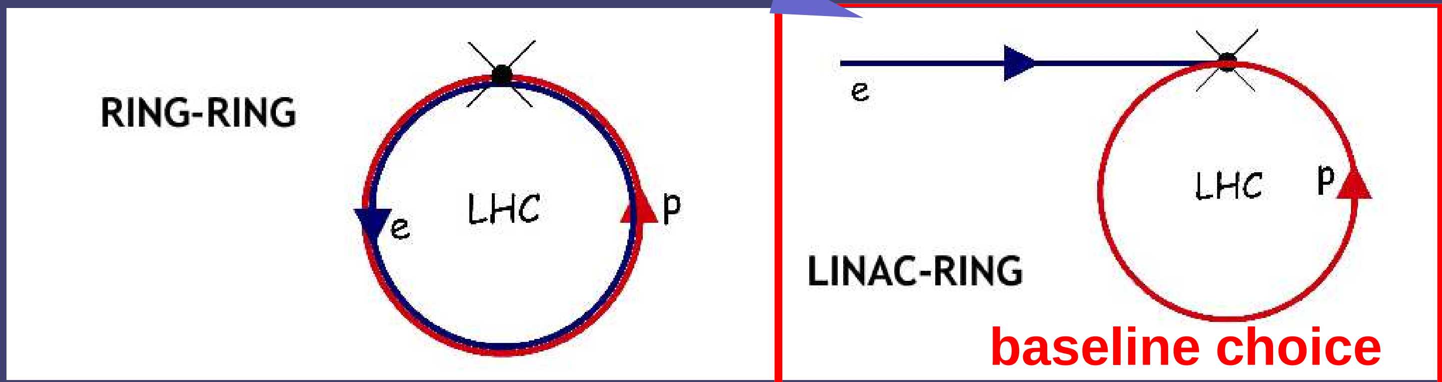


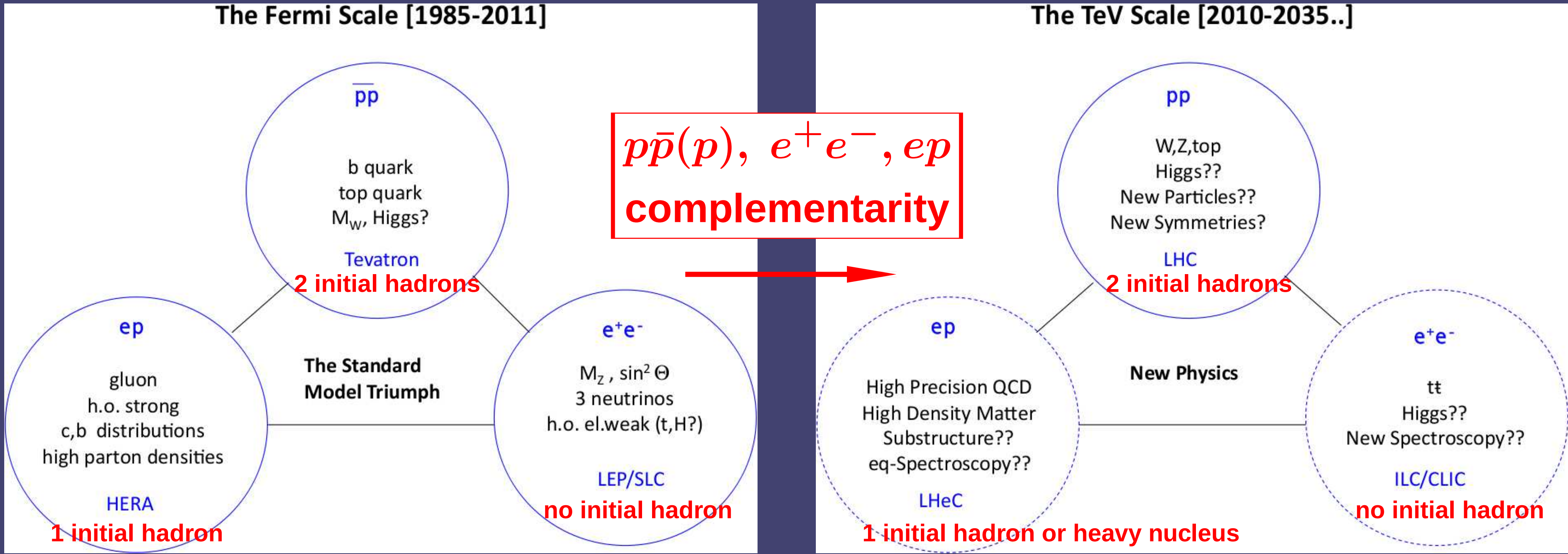
New ERA for ep colliders: LHeC

$E_p = 7$ TeV
$E_e = 50 - 150$ GeV
$\sqrt{s} = 1 - 2$ TeV
$0 \lesssim Q^2 < 10^7$ GeV^2



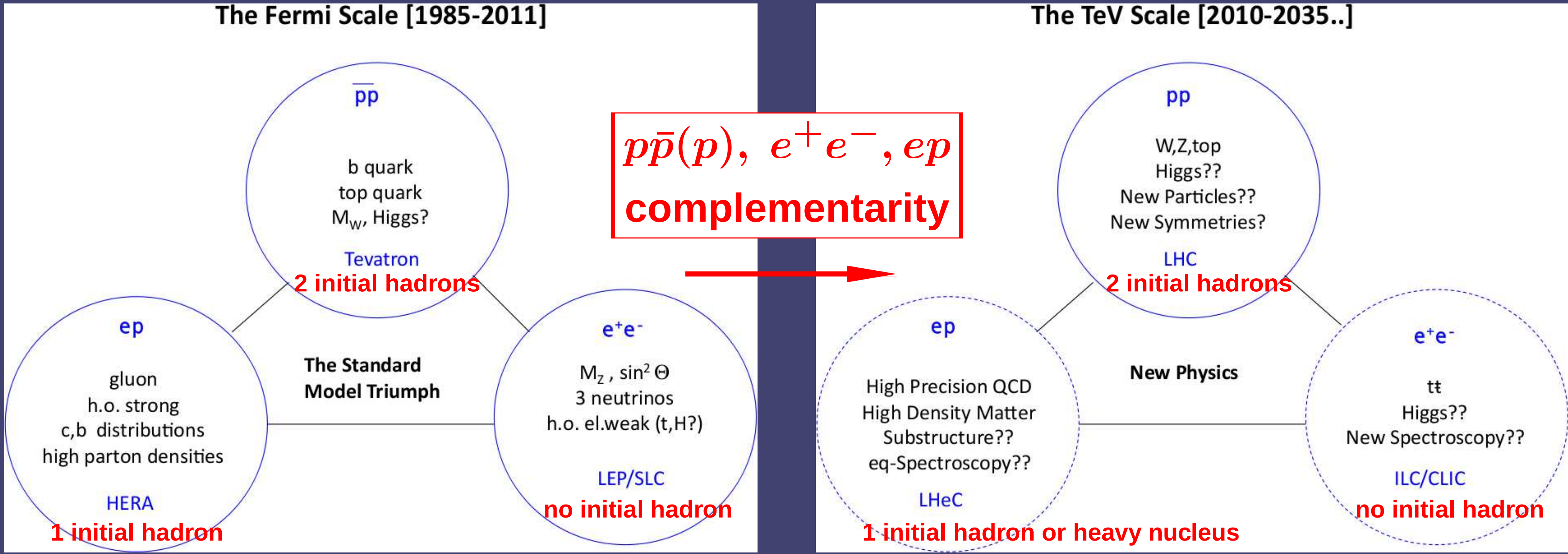
"An option for a future project at CERN" (SPC, July 2010)

LHeC: physics program



- Why an ep/A experiment at TeV energies now ? Exploit complementarity fully for ...
  - resolving the quark structure of the proton
  - mapping the gluon density
  - testing further perturbative QCD
  - searching and understanding new physics
  - investigating the physics of parton saturation
  - providing data which could be of use for future experiments ...

LHeC: physics program



- **Very rich precision physics program within the SM and beyond:**

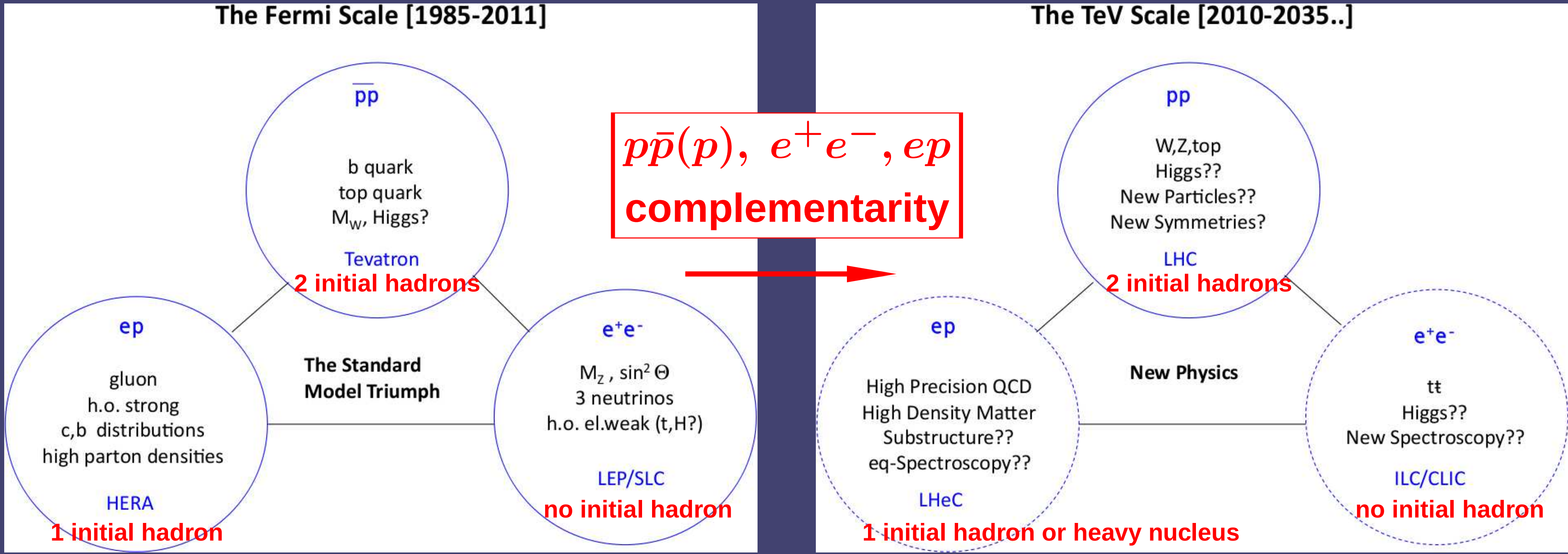
QCD:
- proton structure/PDFs
- photon structure
- heavy flavours
- low x
- α_s
- high P_T jets ...

Electroweak sector:
- top
- Higgs
- HWW coupling
- weak couplings
- mixing angles ...

Physics beyond SM:
- leptoquarks
- quark substructure
- contact interactions
- extra dimensions
- excited leptons ...

Physics with heavy ions...

LHeC: physics program



- **Very rich precision physics program within the SM and beyond:**

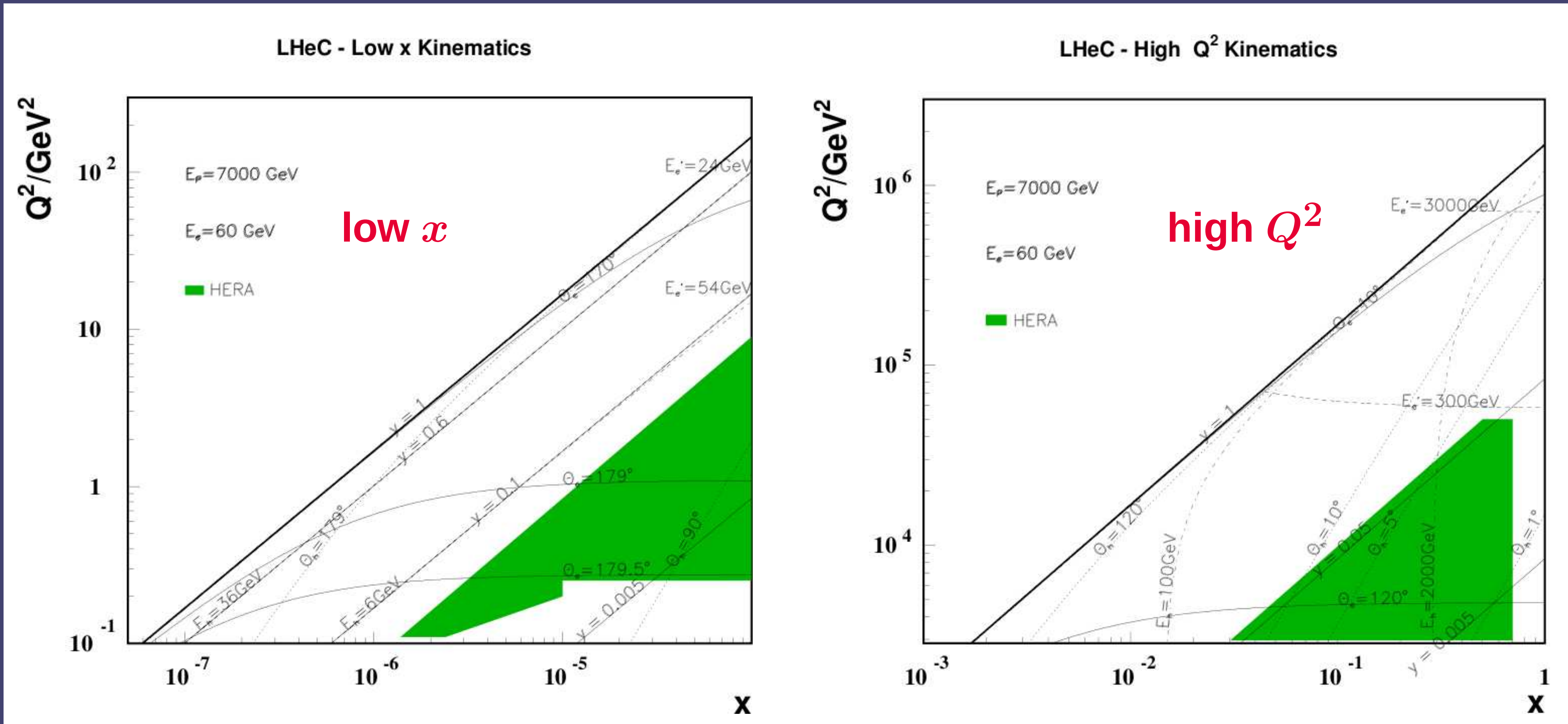
QCD:
- proton structure/PDFs
- photon structure
- heavy flavours
- low x
- α_s
- high P_T jets ...

topics covered in this talk

Other LHeC talks:
- Accelerator: Max Klein
- Detector: Alessandro Polini
- Higgs physics: Uta Klein
- Heavy ions: Paul Newman

LHeC physics: proton structure

- Q^2 vs x kinematic plane for LHeC with $E_p = 7$ TeV and $E_e = 60$ GeV compared to HERA coverage for structure-function/cross section measurements from DIS:



→ much wider coverage available than at HERA, with a large region of overlap:
→ from $Q^2_{\rm max} \approx 0.03$ to 1 TeV^2 and from $x_{\rm min} \approx 4 \cdot 10^{-5}$ to $2 \cdot 10^{-6}$

LHeC physics: proton structure

- The double-differential cross section for inclusive ep scattering is given in terms of the structure functions F_i in NC DIS by

$$\frac{d^2\sigma^{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) \mp Y_-xF_3(x,Q^2) - y^2F_L(x,Q^2)](1+\delta_r(x,Q^2)) =$$

$$= \frac{d^2\sigma_{\mathrm{Born}}}{dx\,dQ^2}(1+\delta_r(x,Q^2))$$

where $Y_\pm = 1 \pm (1-y)^2$
δ_r is the EW radiative correction

- F_2: contains contributions from γ and Z exchange and interference terms; contribution from Z exchange significant only at high Q^2; $F_2 \propto (q+\bar{q})$
- xF_3: parity-violating term arising from Z exchange; sizeable only for $Q^2 > M_Z^2$
- F_L: the longitudinal SF is 0 at LO QCD; at higher orders, F_L is significant only for large y

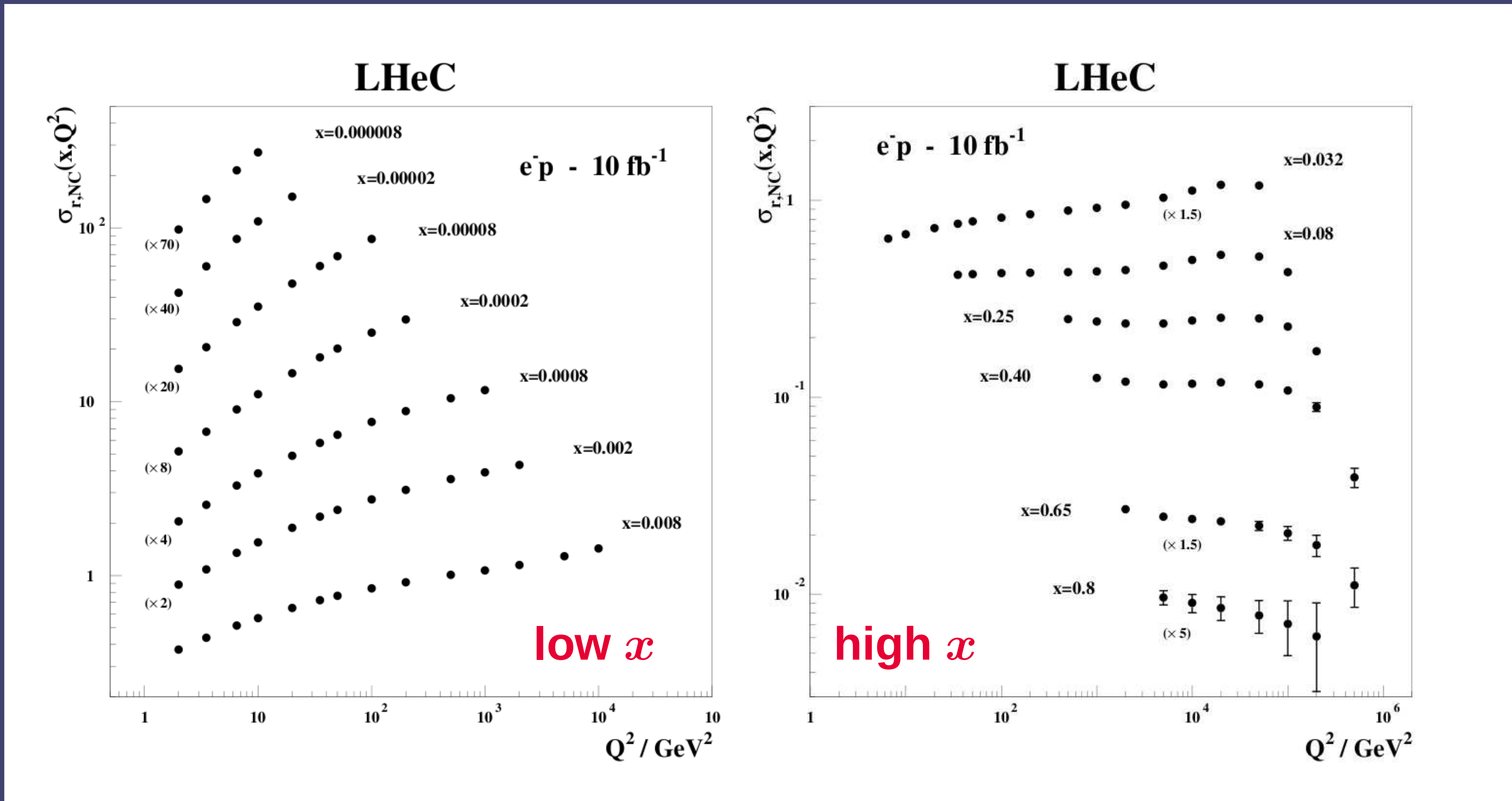
- The reduced cross section is defined as

$$\sigma_r = \frac{xQ^4}{2\pi\alpha^2 Y_+}\frac{d^2\sigma_{\mathrm{Born}}}{dx\,dQ^2}$$

and $\sigma_r \propto F_2$ for $Q^2 \ll M_Z^2$

LHeC physics: proton structure

- Simulation of $e^- p$ NC inclusive reduced cross section measurement for $E_p = 7$ TeV and $E_e = 60$ GeV with $\mathcal{L} = 10$ fb^{-1}:



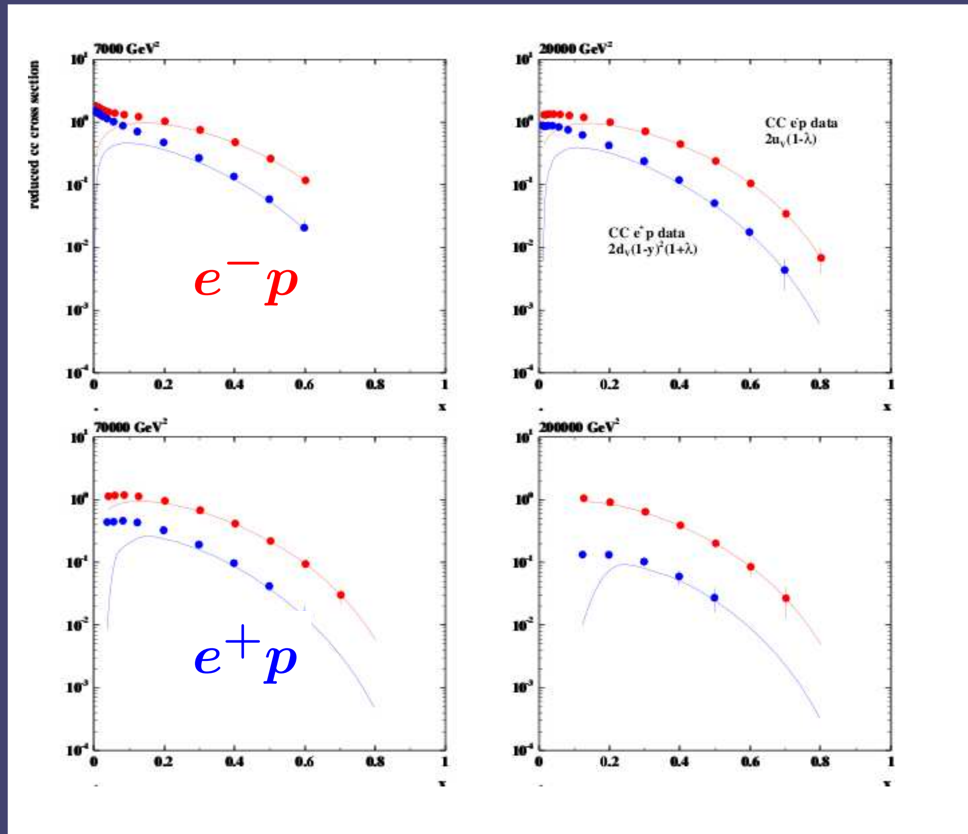
$\rightarrow$ cross sections will be measured with unprecedented precision and range:
$\rightarrow$ predicted uncertainty $\lesssim 1\%$ at low x; at high x/Q^2, statistics dominates

LHeC physics: proton structure

- For longitudinally unpolarised beams,

$$F_2^{CC}(e^+p) = x[d + s + \bar{u} + \bar{c}]$$
$$F_2^{CC}(e^-p) = x[u + c + \bar{d} + \bar{s}]$$

$\Rightarrow$ measurements of $F_2^{CC}(e^{\pm}p)$ give access to flavour content of proton

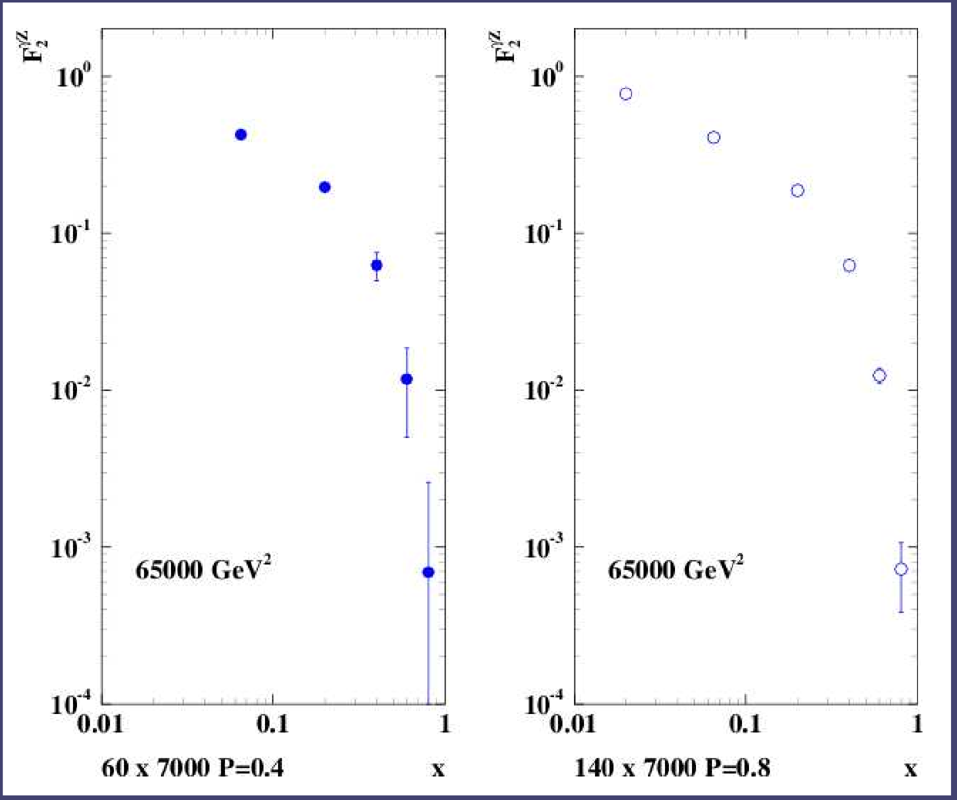


- Simulation of $e^{\pm}p$ CC inclusive reduced cross section measurement for $E_p = 7$ TeV and $E_e = 60$ GeV with $\mathcal{L} = 1$ fb^{-1}:

$\longrightarrow$ cross sections will be measured with unprecedented precision and range:
$\longrightarrow$ a precise determination of the u/d ratio up to large x appears to be feasible at very high Q^2

LHeC physics: proton structure

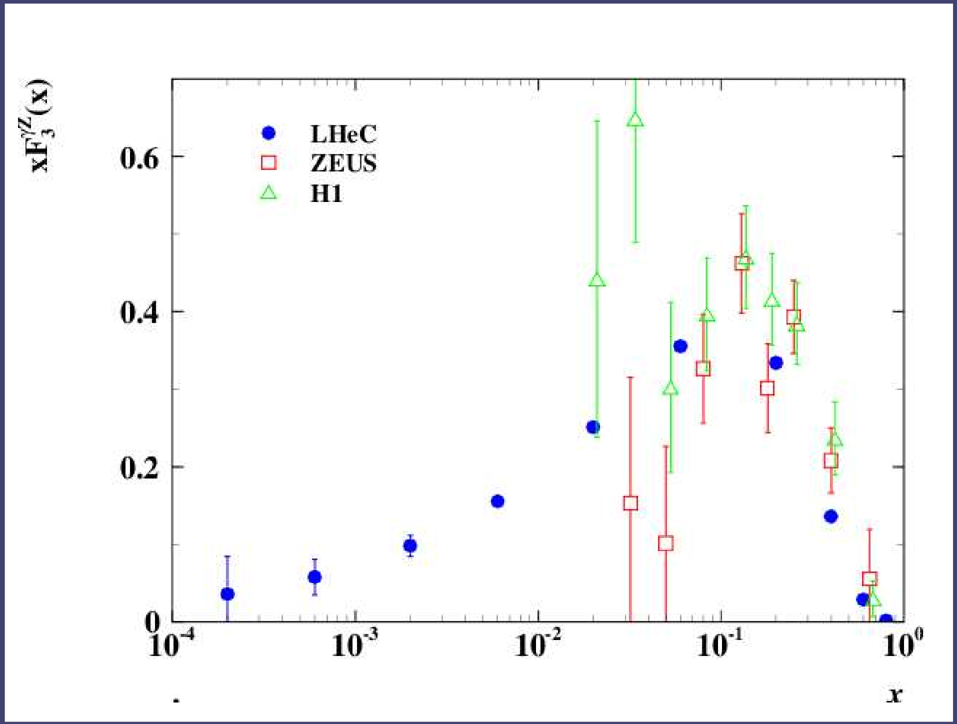
- The interference term in F_2 is given by
$$F_2^{\gamma Z} = x \sum 2 e_q v_q (q + \bar{q})$$
and gives a different quark information than $F_2^{\gamma} (\propto e_q^2)$
- $F_2^{\gamma Z}$ can be measured via NC DIS cross-section asymmetries using polarised beams
- Simulation of $F_2^{\gamma Z}$ measurement for $E_p = 7$ TeV and $E_e = 60/140$ GeV for $\mathcal{L} = 10$ fb^{-1} with different polarisations at $Q^2 = 6.5 \cdot 10^4$ GeV^2:



$\rightarrow$ $F_2^{\gamma Z}$ will be measured with high precision in a wide x range

LHeC physics: proton structure

- The parity-violating structure function is given by
  $xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v + \Delta)$, where Δ is the sea contribution
- Neglecting sea contributions, $$\int_0^1 xF_3^{\gamma Z}\frac{dx}{x} = \frac{1}{3}\int_0^1 (2u_v + d_v)dx = \frac{5}{3}$$
  and gives direct access to the valence quark distributions
- $xF_3^{\gamma Z}$ can be measured via the difference of $e^{\pm}p$ NC DIS cross sections
- Simulation of $xF_3^{\gamma Z}$ measurement for $E_p = 7$ TeV and $E_e = 60$ GeV ($\mathcal{L} = 10$ fb^{-1}) at $Q^2 = 1500$ GeV^2 together with H1 and ZEUS measurements:



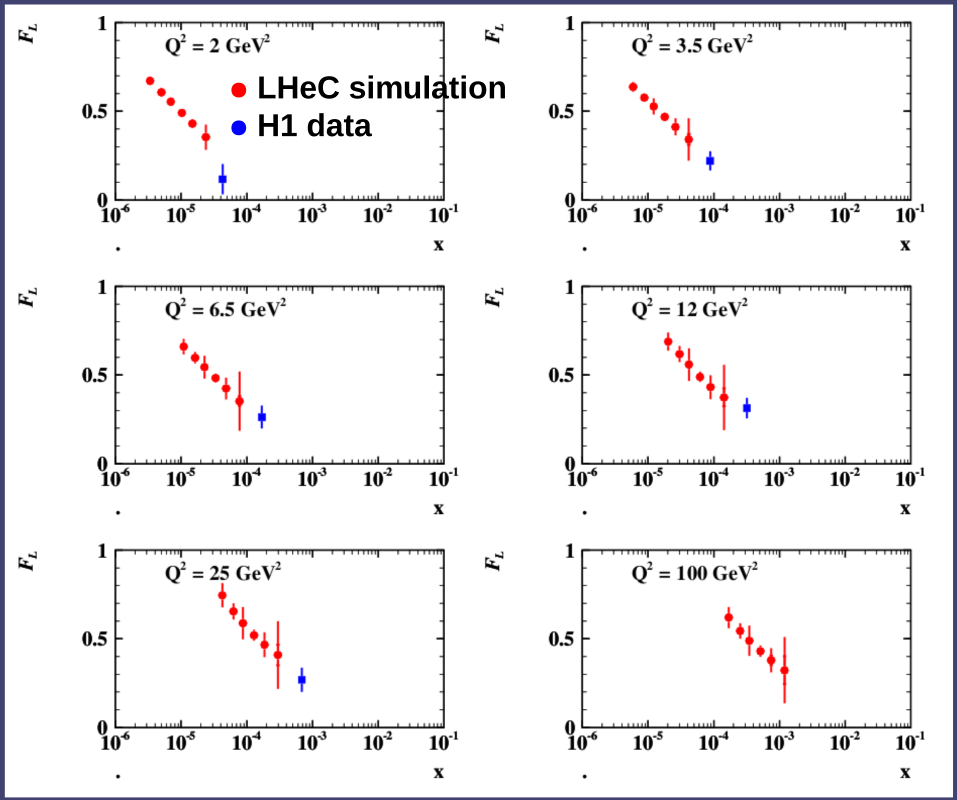
$\rightarrow xF_3^{\gamma Z}$ will be measured with high precision in a wide x range

LHeC physics: proton structure

- The structure function F_L in QCD receives contributions from quarks and gluons
  $\longrightarrow$ at low x, the gluon contribution is dominant
  $\Rightarrow$ F_L is a direct measure of the gluon distribution in the proton
- F_L can be extracted by fits to measurements of σ_r^{NC} at fixed Q^2/x and varying y ($y = Q^2/sx,\ s = 4E_eE_p$)
- Simulation of F_L measurement for $E_p = 7$ TeV and $E_e = 10,\ 20,\ 30,\ 60$ GeV:

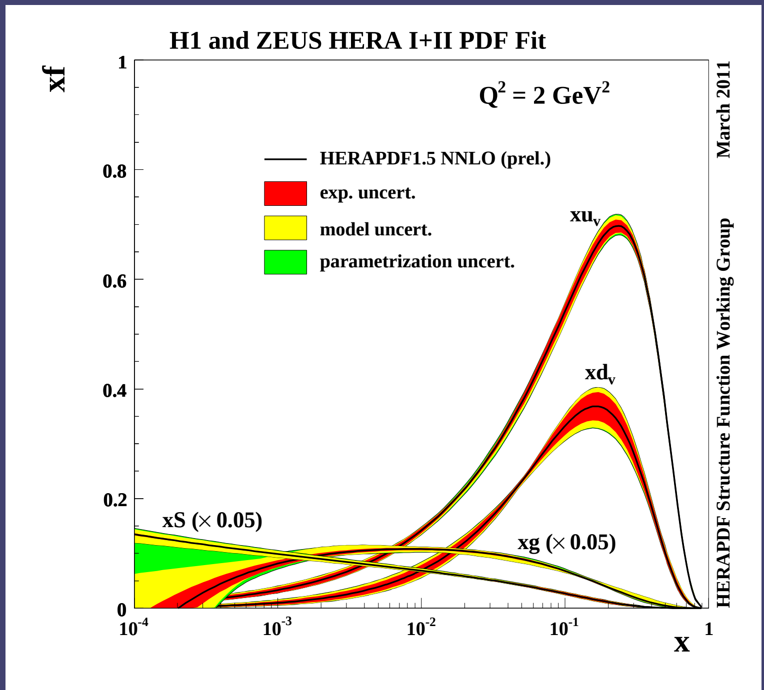
  $\longrightarrow$ the expected accuracy is typically $4\ (7)\%$ at $Q^2 = 3.5\ (25)$ GeV^2

  $\Rightarrow$ the LHeC will provide the first precision measurement of F_L in a region where the behaviour of the gluon density is expected to change significantly

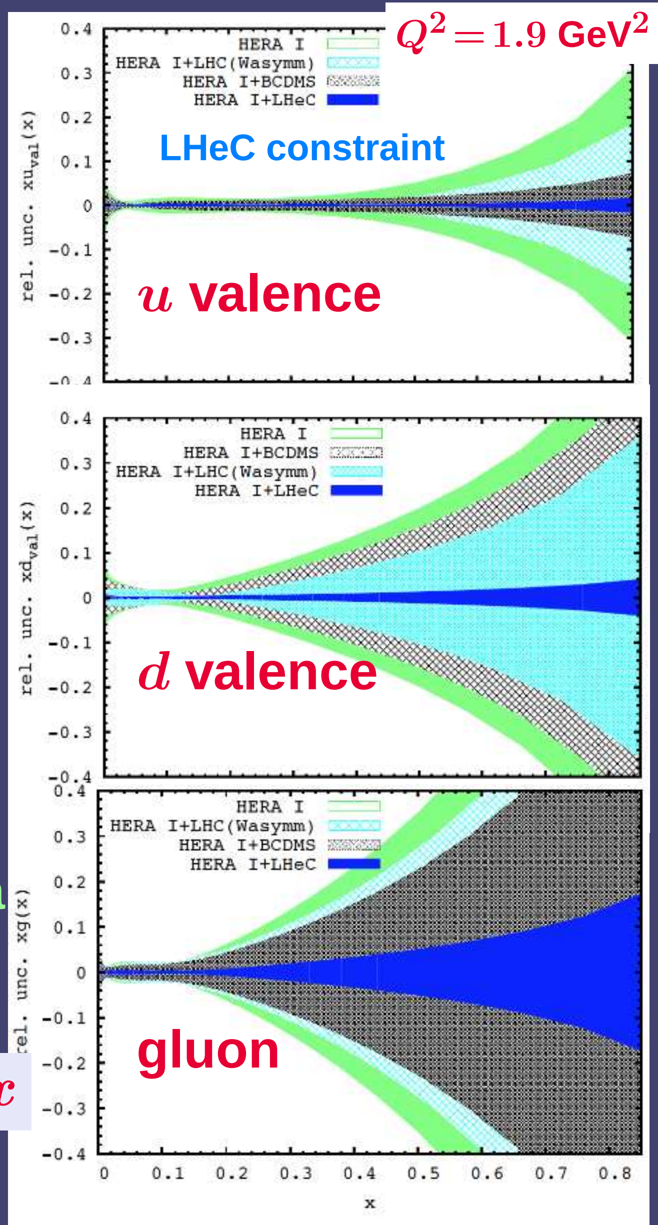


LHeC physics: proton PDFs

- PDFs are extracted from fits to data assuming a functional form for x at a given Q^2_{min} value and then evolved via DGLAP evolution equations
- Current PDF status from HERA:



- Impact of LHeC data expected to be large thanks to
  - new kinematic range
  - huge luminosity
  - polarised beams
  - deuteron beams
  - high precision data



⇒ **LHeC has the potential to provide significant constraints to the PDFs ⟶ high x**

- The reduction of uncertainties in nuclear PDFs are presented in the talk on heavy ions

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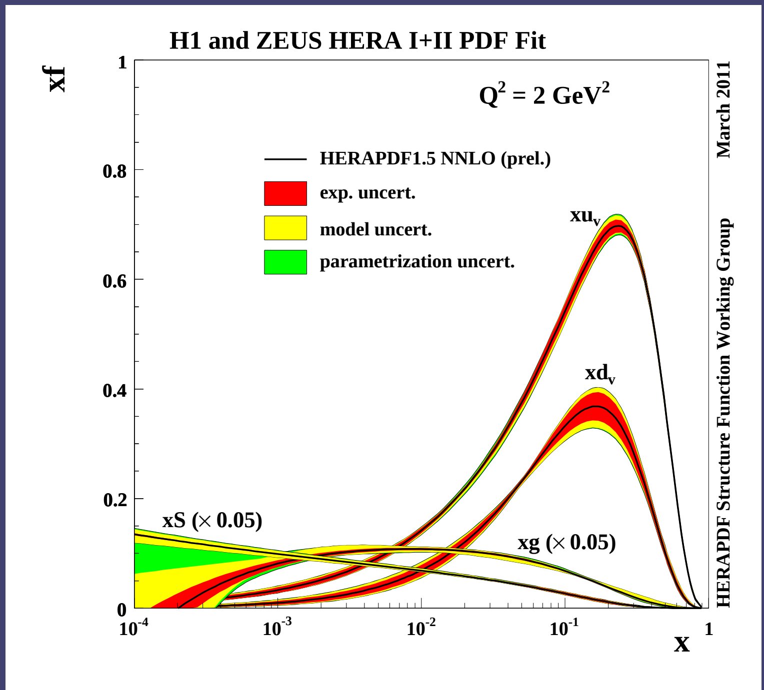

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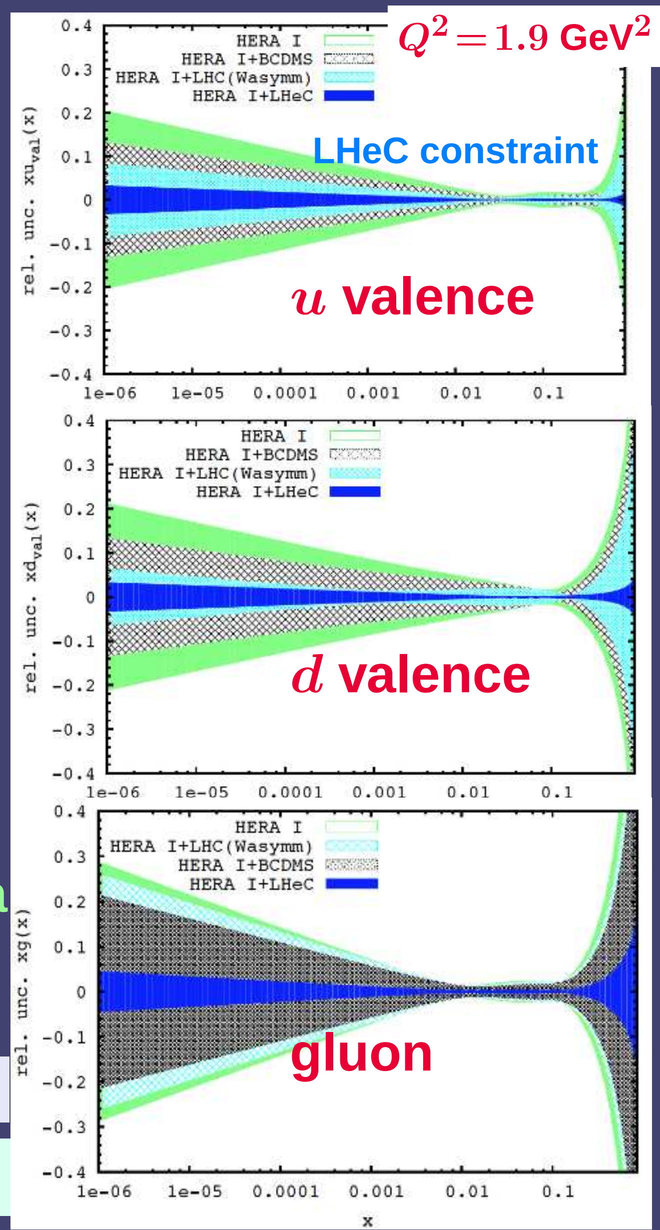
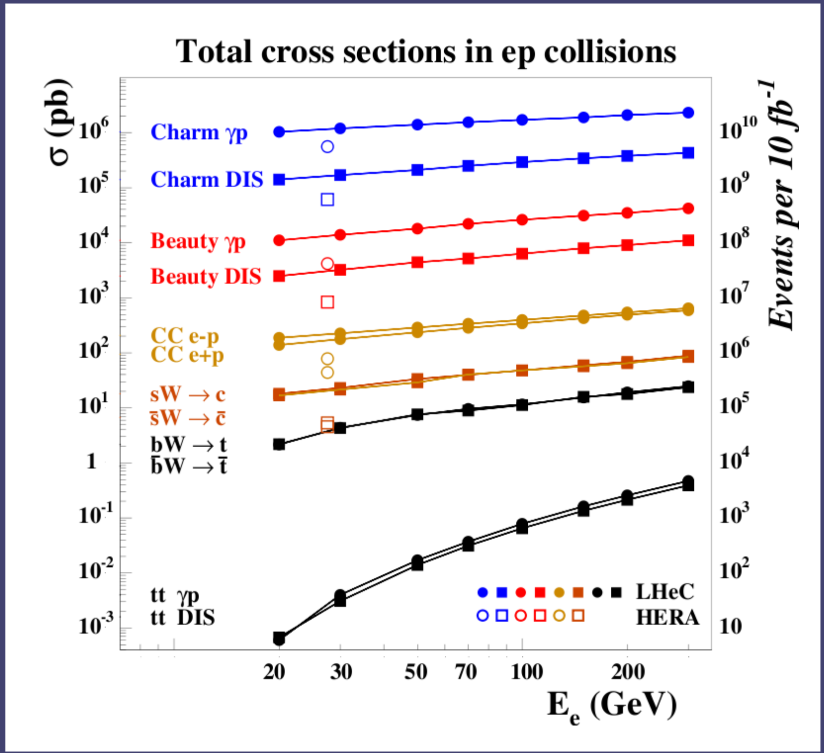


⇒ LHeC has the potential to provide significant constraints to the PDFs → low x

⇒ A precise value of α_s from DIS will also be possible at LHeC

LHeC physics: heavy flavours

- Measurements of heavy-flavour production at HERA provided high-precision pQCD tests and understanding of the dynamics of their production
  $\longrightarrow$ direct sensitivity to gluon density in NC DIS via BGF process
- At LHeC, higher cms energy, larger luminosity and more advanced detector design will extend significantly these studies
- Predicted total cross sections and event rates for 10 fb^{-1} and $E_p = 7$ TeV vs E_e together with calculations for HERA:
  - $\longrightarrow$ LHeC cross sections one order of magnitude larger than at HERA
  - $\longrightarrow$ $s/\bar{s}$ densities will be probed with 10^6 CC events with charm in the final state



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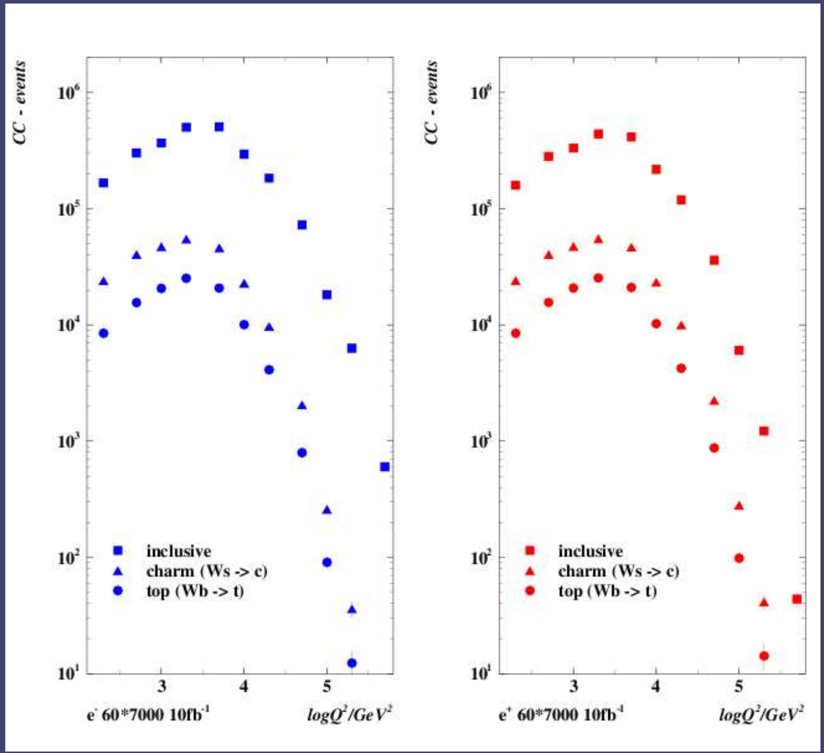
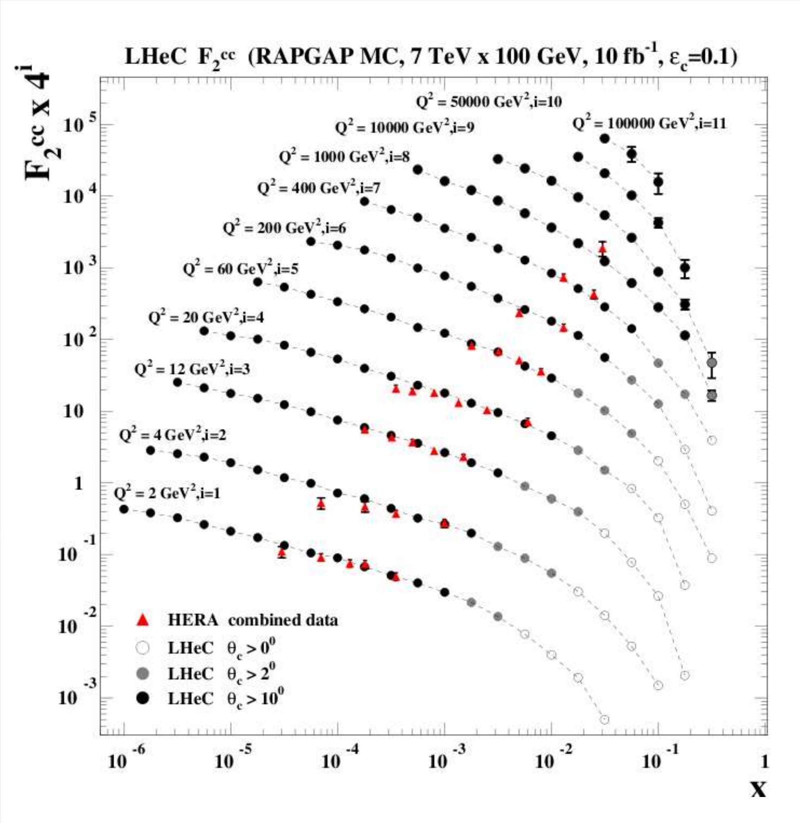
  $\longrightarrow$ $s/\bar{s}$ densities will be probed with 10^6 CC events with charm in the final state
  $\longrightarrow$ top will be probed via single-top production in CC DIS with b in the initial state
  $\longrightarrow$ more than 10^5 events with t in the final state and a similar number of $\bar{t}$ are expected



$\Rightarrow$ **LHeC will give access to all quark flavours with high statistics**

LHeC physics: heavy flavours

- $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ in NC DIS give the contribution from charm and beauty to F_2
- The description of HF production in pQCD is complicated due to the presence of several simultaneous large scales (HF mass, P_T of produced HF and Q^2)
- Several schemes for mass treatment available (FFNS, ZM-VFNS, GM-VFNS)
  $\rightarrow$ treatment of mass terms have implications in global PDF fits and resulting densities
- LHeC data can help to shed light on the ambiguities in this and other HF issues
- Simulation of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ for $E_p = 7$ TeV and $E_e = 100$ GeV for $\mathcal{L} = 10$ fb^{-1} with $m_c = 1.5$ GeV and $m_b = 4.75$ GeV together with HERA data



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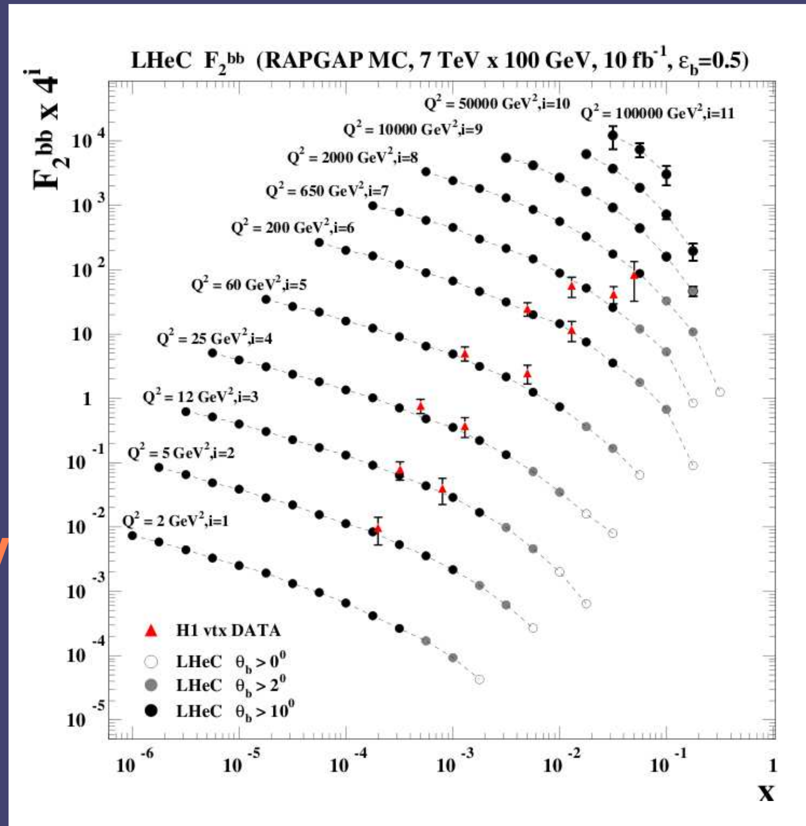
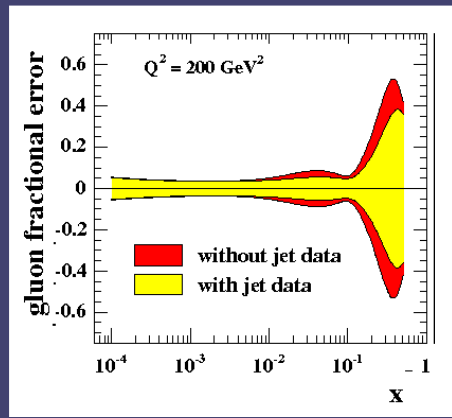


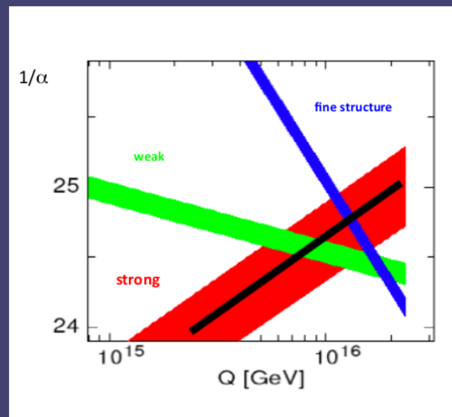
  $\longrightarrow$ much wider phase space available at LHeC extending to very low x at low Q^2 and to higher x at high Q^2
  $\longrightarrow$ statistical precision of LHeC data is very good due to growing cross sections driven by the rise of the gluon density at low x

LHeC physics: high P_T jets

- The study of high P_T jets in DIS and photoproduction provides a testing ground for pQCD and sensitivity to α_s and the proton/photon PDFs
  $\longrightarrow$ high-precision jet cross-section measurements from HERA have yielded
  - ⋆ sizeable constraints on the gluon density of the proton at medium to high x
    $\longrightarrow$ jet cross sections are directly sensitive to the gluon in the proton via BGF process



  - ⋆ α_s determinations with an accuracy of $\mathcal{O}(3-4\%)$ (uncertainty mostly dominated by theory)
    $\longrightarrow$ α_s is the least known of the couplings ($\Delta\alpha_s(\mathrm{WA}) = 0.6\%$)
    $\longrightarrow$ $\Delta\alpha_s$ has influence on GUT and translates into uncertainty on PDFs and hadronic cross sections
    $\longrightarrow$ unresolved issue: $\alpha_s(\mathrm{DIS}) < \alpha_s(\mathrm{WA}) < \alpha_s(\mathrm{jets})$
    $\longrightarrow$ precision data from LHeC should help understanding

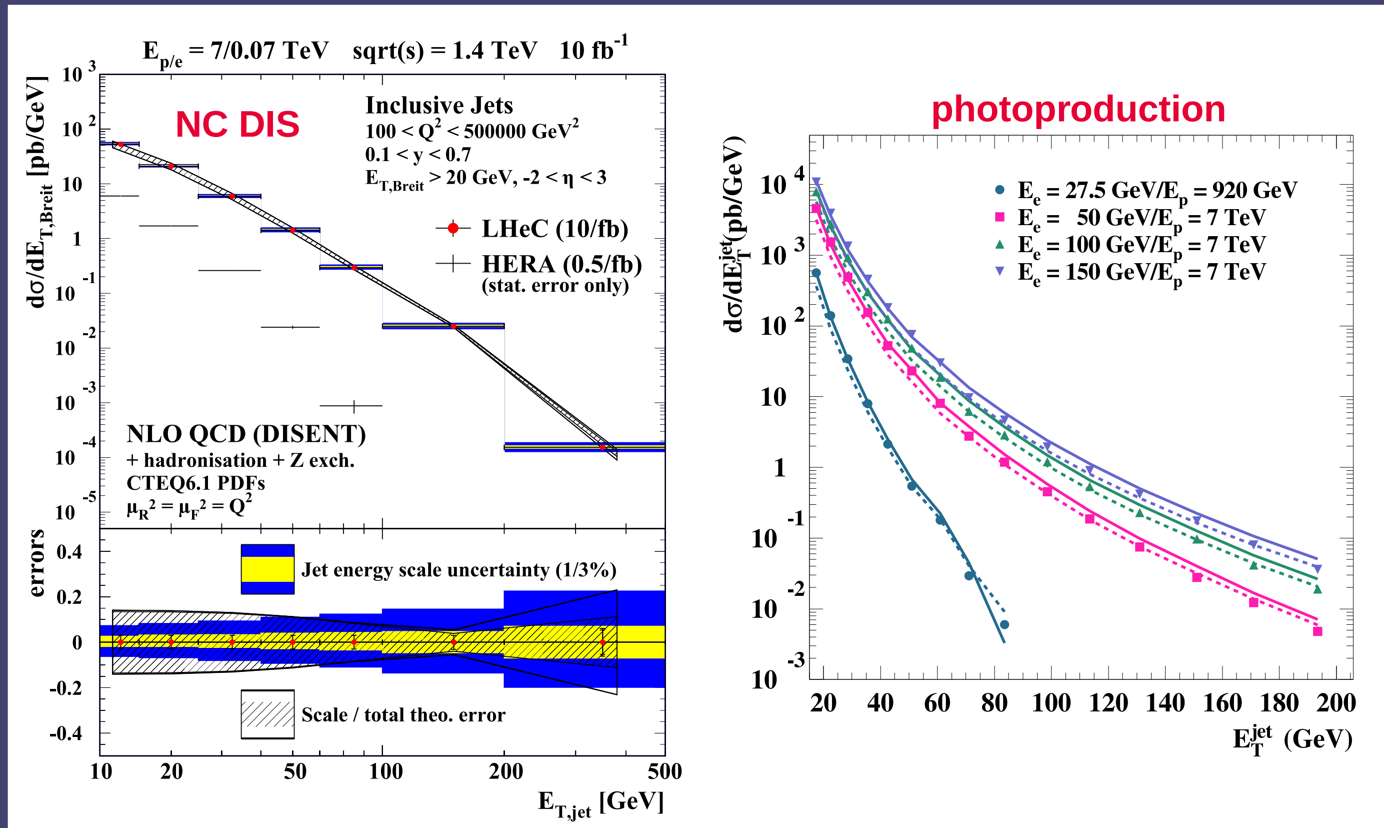


  - ⋆ potential to constrain the photon PDFs
    $\longrightarrow$ photon PDFs very poorly constrained
    $\longrightarrow$ crucial understanding for future e^+e^- accelerators (ILC/CLIC) since $\gamma\gamma$ collisions will provide a huge background for cms energies far above M_Z

LHeC physics: high P_T jets

- Predicted inclusive-jet cross sections vs $E_T^{\rm jet}$ for $E_p = 7$ TeV and various E_e for $\mathcal{L} = 10$ fb^{-1} together with calculations for HERA:

- A much wider kinematic range, high luminosity and more advanced detector design will allow very high-precision data

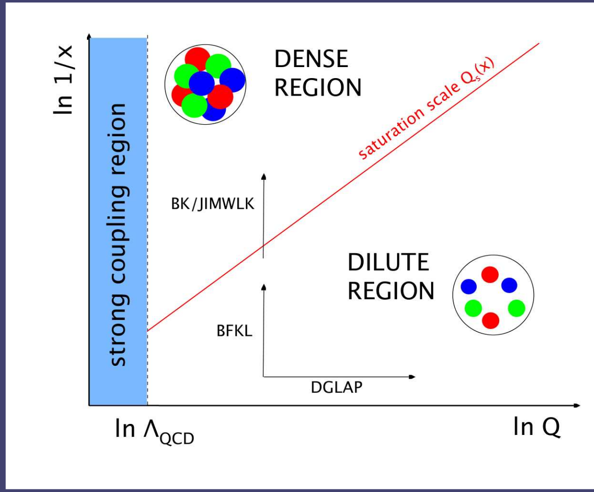


⇒ **Impact of LHeC jet measurements on pPDFs and α_s is expected to be large**

- The accuracy of α_s and the constraints on the PDFs will also benefit enormously from NNLO calculations of jet cross sections in ep

LHeC physics: low x physics

- Up to now, QCD studies at LHeC shown within the framework of fixed-order perturbation theory and collinear factorisation (DGLAP), valid for high Q^2/x, but CF expected to break down at low x
  $\longrightarrow$ in DGLAP, parton densities expected to rise at small x (proton increasingly packed at low x) $\longrightarrow$ rise at low x observed at HERA
- New phenomena predicted at high parton densities
  $\longrightarrow$ linear small-x resummation
  $\longrightarrow$ non-linear evolution
  $\longrightarrow$ parton saturation
- These effects would lead to deviations from DGLAP evolution at low x $\longrightarrow$ some hints of such deviations were already observed in low-x HERA data

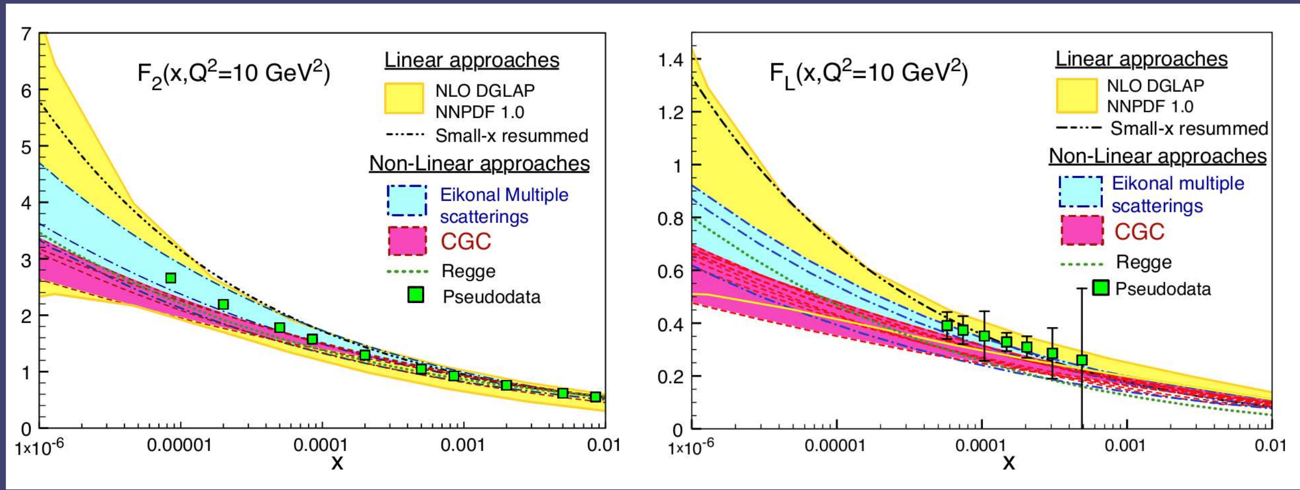


$\Rightarrow$ The low-x region is an exciting and largely unexplored territory

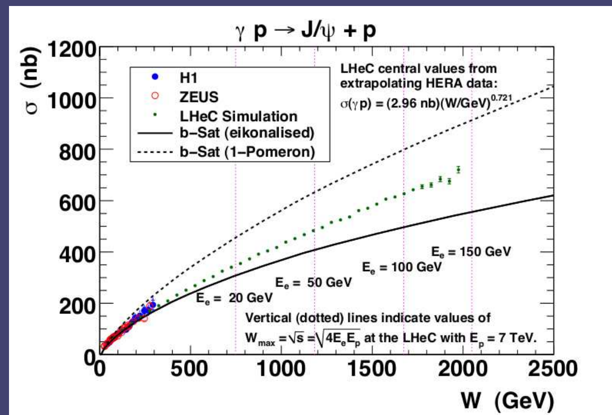
$\Rightarrow$ LHeC: ideal machine to study low-x regime and its non-perturbative dynamics at sufficiently large Q^2, the transition towards a new state of dense QCD matter and to favour/disfavour the proposed models (eg dipole model) which aim to describe this kinematic region, by measuring at very low x and/or scattering off heavy nuclei

LHeC physics: low x physics

- Precise LHeC data on $F_2,\ F_L$ discriminate between different models and constrain the dynamics at low x
  $\longrightarrow$ simultaneous description of BOTH $F_2,\ F_L$ crucial

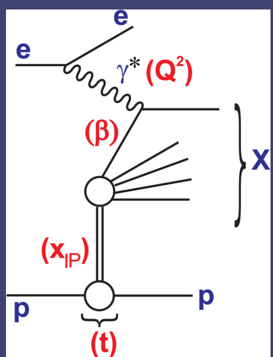


- Exclusive production of vector mesons provide complementary information to that from inclusive measurements, as they are sensitive to the square of the gluon density
  $\longrightarrow$ J/ψ production is a potentially very clean probe of the gluonic structure and is particularly sensitive to unitarity effects

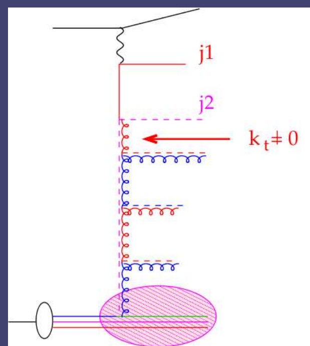


- Other important probes of low-x dynamics include

diffraction



forward-jet production



Summary

- Many important aspects of the rich physics program on QCD have been reviewed
  → proton structure and PDFs, heavy flavours, high P_T jets and low-x dynamics

★ The LHeC will be able to explore a new kinematic regime at high luminosity and provide information to
  → constrain the proton parton distributions
  → explore the new kinematic regime of low x and moderate-to-high Q^2
  → test further pQCD and the electroweak sector
  → search for new physics
  → physics with heavy ions
  → provide data to be used in future experiments

★ The experimental prospects challenge theory and require a continued feed-back between experimentalists and theoreticians

- The LHeC has passed a major milestone with a refereed CDR, supported and monitored by CERN, ECFA and NuPECC, published by The LHeC Study Group
  → JL Abelleira Fernandez et al, "A Large Hadron Electron Collider at CERN" CERN-OPEN-2012-015, arXiv:1206.2913, submitted to J Phys G (2012)
  → Collaborations soon to be built for further design of machine and detector