Physics Highlights

of a

Future eP/eA Collider

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HISTORY

EP option proposed since the beginning of the LHC

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

CERN-ECFA workshop, Lausanne, March 1984:
a Large Hadron Collider in the LEP tunnel
- **LHeC**: CDR PUBLISHED IN 2012

- **EIC**: “APPROVED AS A CONSTRUCTION RECOMMENDATION” BY NSAC OCT. 2015

(CEIC2 no longer considered; MEIC2 lumi now $2 - 5 \times 10^{34}$; HL-RHIC lumi now $2 - 3 \times 10^{34}$)
THE LHeC

• **RECIRCULATING LINAC WITH ENERGY RECOVERY**
  → **THREE ACCELERATING PASSES THROUGH EACH OF TWO 10 GeV LINACS**
  ⇒ 60 GeV ELECTRON BEAM

• **COLLISIONS WITH ONE HL-LHC BEAM** *(PROTON OR ION)*

**BASELINE PARAMETERS**

<table>
<thead>
<tr>
<th>10^{34} cm^{-2}s^{-1} Luminosity reach</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity [10^{33}cm^{-2}s^{-1}]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Normalized emittance γ_{x,y} [μm]</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Beta Funtion β_{x,y} [m]</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>rms Beam size σ_{x,y} [μm]</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>rms Beam divergence σ'_{x,y} [μrad]</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>1112</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>2.2*10^{11}</td>
<td>4*10^9</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
</tr>
</tbody>
</table>
THE LHeC DETECTOR

Baseline Detector

- Forward / backward asymmetry reflecting beam energies
- Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- e/γ taggers ZDC, proton spectrometer integral to design from outset system providing tagging, no independent momentum measurement
**LHeC: KINEMATIC COVERAGE**

**DEEP-INELASTIC SCATTERING**

- **VERY SMALL MOMENTUM FRACTIONS** $x \lesssim 10^{-6}$ REACHED AT **LOW SCALE** $Q \sim 1$ GeV
- **VERY LARGE SCALE** $Q \sim 1$ TeV REACHED AT **LARGE** $x \sim 0.5$
- **VERY LARGE** $x \sim 0.9$ REACHED IN **WIDE RANGE** OF SCALES $10 \lesssim Q \lesssim 1000$ GeV
THE EIC

- TWO BASIC DESIGNS (JLAB vs. BNL); ENERGY-LUMI TRADEOFF
- \( e \) BEAM: 5 – 10 GeV; VARIABLE CM ENERGY: 20 – 100 GeV
- LUMI \( 10^{33} – 10^{34} \text{ cm}^{-2} \text{ sec}^{-1} \)
- POLARIZED BEAMS AVAILABLE WITH \( e, p, d, ^3He \)
- WIDE RANGE OF NUCLEI FOR UNPOL. \( eA \); LUMI PER NUCLEON SAME AS FOR \( e-p \)
EIC: KINEMATIC COVERAGE

DEEP-INELASTIC SCATTERING

- SOMewhat LOWER ENERGY IN COMPARISON TO HERA

- MAIN STRENGTHS: POLARIZATION AND VARIETY OF NUCLEAR TARGETS

- POLARIZATION: UNIQUE OPTION
PHYSICS AT THE LHeC

• PARTON DISTRIBUTIONS
  – PDF UNCERTAINTIES AT NNLO AND BEYOND
  – $\alpha_s$
  – NUCLEAR PDFS

• PRECISION PHYSICS OF THE SM AND BEYOND
  – HIGGS COUPLINGS ($b$ AND $c$) AND CP
  – SINGLE TOP (FCNC, $V_{tb}$)
  – THE WEAK MIXING ANGLE

• “ALICE” PHYSICS
  – HIGH DENSITY QCD & SATURATION
  – DIFFRACTION
PARTON DISTRIBUTIONS
## WHY WORRY ABOUT PDFs?

**Higgs Production**

<table>
<thead>
<tr>
<th>Process</th>
<th>σ (8 TeV)</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg → H</td>
<td>19.5 pb</td>
<td>14.7%</td>
</tr>
<tr>
<td>VBF</td>
<td>1.56 pb</td>
<td>2.9%</td>
</tr>
<tr>
<td>WH</td>
<td>0.70 pb</td>
<td>3.9%</td>
</tr>
<tr>
<td>ZH</td>
<td>0.39 pb</td>
<td>5.1%</td>
</tr>
<tr>
<td>ttH</td>
<td>0.13 pb</td>
<td>14.4%</td>
</tr>
</tbody>
</table>

*NNLL QCD + NLO EW* and *NNLO QCD + NLO EW*

*(J. Campbell, HCP2012)*

**PDF Uncertainty either dominant, or very large, or both**

...and not only for the Higgs!

(*W* mass determination, new physics searches for heavy states,...)
PDFs TODAY:
KINEMATIC COVERAGE

NNPDF3.0 NLO dataset
PDFs TODAY:
PDFS & UNCERTAINTIES

- **LOWEST PDF UNCERTAINTIES** $\sim 5\%$: $\Rightarrow$ **GLUON AT SMALL $x$, VALENCE AT MEDIUM-LARGE $x$**

- **STRANGE AND SEA LESS WELL KNOWN**

- **LARGE UNCERTAINTIES** AT SMALL AND LARGE $x$
PDFs TODAY: PARTON LUMINOSITIES

- CAN READ OFF PDF UNCERTAINTY

- UNCERTAINTIES BLOW UP FOR LIGHT ($\sim 10$ GeV) AND HEAVY ($\gtrsim 1$ TeV) FINAL STATES
HERA AND LHC DATA: WHAT IS THE RELATIVE IMPACT?

COMPARE PDF DETERMINED FROM FULL GLOBAL FIT, NO LHC DATA, ONLY HERA DATA:

- IN REGIONS WHERE HERA DATA AVAILABLE, HERA ONLY UNCERTAINTY QUALITATIVELY COMPARABLE TO THAT OF GLOBAL FIT
- IMPACT OF LHC DATA MODERATE
- DIS DATA DRIVE THE GLOBAL FIT
HERA AND LHC DATA: WHAT IS THE RELATIVE IMPACT?

- **OVERALL MEASURE OF IMPACT:**
  \[ \varphi \rightarrow \text{FIT UNCERTAINTY/DATA UNCERTAINTY} \]

- **HERA-II IMPACT SIZABLE**

- **IMPACT OF LHC DATA MODERATE BUT VISIBLE**

- **IMPACT OF CMS OR ATLAS COMPARABLE TO (MODERATE) IMPACT OF NON-LHC, NON-HERA DATA**

### FRACTIONAL UNCERTAINTY

<table>
<thead>
<tr>
<th>Dataset</th>
<th>( \varphi ) NLO</th>
<th>( \varphi ) NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>0.291</td>
<td>0.302</td>
</tr>
<tr>
<td>HERA-I</td>
<td>0.453</td>
<td>0.439</td>
</tr>
<tr>
<td>HERA all</td>
<td>0.375</td>
<td>0.343</td>
</tr>
<tr>
<td>HERA+ATLAS</td>
<td>0.391</td>
<td>0.318</td>
</tr>
<tr>
<td>HERA+CMS</td>
<td>0.315</td>
<td>0.345</td>
</tr>
<tr>
<td>no LHC</td>
<td>0.312</td>
<td>0.316</td>
</tr>
</tbody>
</table>

**THE GLUON**

**GLOBAL VS NO LHC**

- NNLO, \( \alpha_s = 0.118 \), \( Q^2 = 10^4 \text{ GeV}^2 \)

**GLOBAL VS HERA+CMS**

- NNLO, \( \alpha_s = 0.118 \), \( Q^2 = 10^4 \text{ GeV}^2 \)
PDFS AT LHC RUN II

- DATA AT HIGHER CM ENERGY & INFO ON CORRELATION TO LOW ENERGY → EXTENDED KINEMATIC COVERAGE & REDUCED SYSTEMATICS
- EXPECT REDUCTION IN MODEL DEPENDENCE
- MODERATE REDUCTION IN UNCERTAINTY

GLUON
CTEQ AFTER RUN II

NOW
NNLO, $Q^2 = 100$ GeV$^2$

NPDF AFTER RUN II

$Q^2 = 10000$ GeV$^2$

(PDF4LHC: 1507.00556)

VERY DIFFICULT TO REDUCE UNCERTAINTIES BELOW 3-4% LEVEL
AT A HADRON COLLIDER
**PDFS AT THE LHeC**

- **UNCERTAINTIES DOWN TO PERCENT LEVEL IN WIDE KINEMATIC REGION**
- **WITH DEUTERON BEAMS, FULL LIGHT FLAVOR DECOMPOSITION**
- **THANKS TO HIGH ENERGY, NC+CC ⇒ PRECISION STRANGENESS DETERMINATION**

**GLUON**

(A. Cooper-Sarkar & Voica Radescu, 2015)

WITH THE LHeC, PDF UNCERTAINTY ON HIGGS PRODUCTION CHANNELS ESSENTIALLY REMOVED (PART OF BACKGROUND NOISE)
NUCLEAR PDFS AT THE LHeC (AND EIC)

NPDFs at the LHeC

- **Huge enlargement in kinematic region**
- **Huge increase in precision at small $x$**
- **EIC performance similar but at lower energy**

NPDFs at the EIC
**$N^3$LO PDFs:**

- **NEEDED AT THE 1% ACCURACY LEVEL**

- **IMPACT OF $N^3$LO DEPENDS ON PROCESS:**
  - **Higgs Gluon Fusion:** perturbative dep. of PDF negligible in comparison to matrix element $\Rightarrow$ $N^3$LO NOT NEEDED
  - **Top:** perturbative dep. of PDF smaller, but not negligible in comparison to matrix element, anticorrelated to it $\Rightarrow$ $N^3$LO NECESSARY

**SCALE UNCERTAINTY & DEP. ON PERTURBATIVE ORDER**

**Higgs**

<table>
<thead>
<tr>
<th>XS order</th>
<th>LO</th>
<th>NLO</th>
<th>NNLO</th>
<th>$N^3$LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ [pb]</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

- **N$^3$LO DIS COEFFICIENT FUNCTIONS KNOWN**
- **BOTTLENECK:** $N^3$LO ANOMALOUS DIMENSIONS
- **N$^3$LO Jets UNLIKELY TO BE AVAILABLE ANY TIME SOON**

(s.f., Isgrò, Vita, 2014)
THE VALUE OF $\alpha_s$

- PDG VALUE (AUGUST 2014): $\alpha_s(M_Z) = 0.1185 \pm 0.0006$

- HXSWG/PDF4LHC RECOMMENDS $\alpha_s(M_Z) = 0.118 \pm 0.0015$

- THIS IS A $\sim 5\%$ UNCERTAINTY ON HIGGS IN GLUON FUSION PROGRESS EXPECTED?

- PDG IS AN AN AVERAGE OF AVERAGES, SOME OF WHICH INCLUDE MUTUALLY INCONSISTENT VALUES BY UP TO FOUR-FIVE $\sigma$

- LITTLE PROGRESS FOR MANY YEARS: PDG 1998-2006 $\Delta \alpha_s(M_Z) = 0.002$; PDG 2010-2014 $\Delta \alpha_s(M_Z) = 0.0006 \div 0.0008$ (CHANGE OF AUTHOR)

$\alpha_s$ AT THE LHeC

- ACCURATE SIMULTANEOUS DETERMINATION OF $\alpha_s$ AND THE GLUON POSSIBLE THANKS TO BIG LEVER ARM IN $Q^2$

- LONG-STANDING ISSUE WITH $\alpha_s$ FROM DIS CAN BE RESOLVED
**PDFs: SUMMARY**

- **ACCURATE PDFs required both for precision and discovery.**

- **WITHOUT LHeC extremely difficult to go below 3% uncertainty in precision physics region.**

- **WITHOUT LHeC extremely difficult to reduce current 100% uncertainty in discovery region.**

- **WITHOUT LHeC extremely difficult to reduce current 1-2% uncertainty on $\alpha_s$.**

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**Higgs in gluon fusion: Now**

$ggH, ggHiggs$ NNLO, LHC 13 TeV, $\alpha_s = 0.118$

<table>
<thead>
<tr>
<th>Cross-Section (pb)</th>
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<tbody>
<tr>
<td>40</td>
</tr>
<tr>
<td>40.5</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>41.5</td>
</tr>
<tr>
<td>42</td>
</tr>
<tr>
<td>42.5</td>
</tr>
<tr>
<td>43</td>
</tr>
<tr>
<td>43.5</td>
</tr>
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**Gluino production: with or w/o LHeC**

LHC (14 TeV)
PRECISION PHYSICS
HIGGS PRODUCTION
EP VS. PP

- Higgs produced in CC or NC interactions
- Clean signal and $ZZH$ vs. $WWH$ separation $\Rightarrow$ probe of HWW vertex $\Rightarrow$ Higgs CP properties
- Direction of FS quark well defined $\Rightarrow$ accurate $b\bar{b}$ decay measurement
HIGGS PHYSICS AT THE LHeC
TENSOR COUPLINGS TO WW

- PARAMETRIZE $HWW$ VERTEX AS
  \[ \gamma^{\mu \nu} = -g^{\mu \nu} + \frac{1}{m_W^2} \left[ \lambda (p_1 \cdot p_2 g^{\mu \nu} - p_1^\mu p_2^\nu) + i \lambda' \epsilon^{\mu \nu \rho \sigma} \right] \]; SM: $\lambda = \lambda' = 0$

- MEASURE AZIMUTHAL DISTRIBUTION BETWEEN NEUTRINO ($E_{t \text{miss}}$) & JETS → SENSITIVE PROBE OF Higgs CP PROPERTIES
HIGGS PHYSICS AT THE LHeC
THE $H^{bb}$ COUPLING

- FORWARD JET TAGGING $\Rightarrow$ VERY CLEAN SIGNAL AGAINST SMALL $\bar{b}bj$ NC & CC BACKGROUND WITH CUT-BASED ANALYSIS

- MEASURE COUPLING WITH 4% PRECISION WITH $100 \text{ fb}^{-1}$
  $10 \text{ fb}^{-1} = \text{one month} = 1100 H \rightarrow bb$ events

- $\tau\tau$ ABOUT 10% PRECISION; EVEN $\bar{c}c$ MEASURABLE
HIGGS PHYSICS AT THE LHeC
SUMMARY

- **GLUON FUSION AND W FUSION** ⇒ PDF + $\alpha_s$ UNCERTAINTY REMOVED (hatched bands)

- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;

- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE
TOP PHYSICS AT THE LHeC
THE $V_{tb}$ CKM MATRIX ELEMENT

- CLEAN DEEP-INELASTIC SINGLE TOP PRODUCTION
- $100 \text{ fb}^{-1} \Rightarrow \sim 10^6$ SINGLE TOP DIS EVENTS
  $\Rightarrow \Delta V_{tb} = 0.005$ PRECISION

LHeC, $100 \text{ fb}^{-1}$
$1.000 \pm 0.005$ (expected)
TOP PHYSICS AT THE LHeC

- CLEAN DEEP-INELASTIC SINGLE TOP PRODUCTION
- TEST ANOMALOUS COUPLINGS
- $100 \text{ fb}^{-1} \Rightarrow \sim 10^6$ SINGLE TOP DIS EVENTS
  $\Rightarrow$ FCNC $O\left(\frac{\kappa}{\Lambda}\right)$; $\Lambda = 1 \text{ TeV}$, DISCOVERY FOR $\kappa \sim 10^{-3}$
THE ELECTROWEAK MIXING ANGLE

- CAN EXTRACT $\sin^2 \theta_W$ FROM CC/NC DIS RATIOS & FROM SEPARATION OF $\gamma Z$ INTERFERENCE FROM PURE $Z$ EXCHANGE ($e^+ \text{ vs. } e^-$ DIS)

- CAN MEASURE MIXING ANGLE FOR SEVERAL $Q^2$ VALUES TO HIGH ACCURACY ⇒ TEST OF SCALE DEPENDENCE

LHeC(FCC-eh)
- Sensitivity from:
  - $A_{LR}$ at high $Q^2$
  - $\sigma_{NC}/\sigma_{CC}$ at lower $Q^2$
“ALICE” PHYSICS
LHeC: THE MECCA OF HIGH-DENSITY QCD

- “LINEAR” ALTARELLI-PARISI EVOLUTION: AT LOW MOMENTUM FRACTION, GLUON AND SEA PDFS RISE ⇒ UNITARITY VIOLATION?
- PARTON RECOMBINATION SETS IN ⇒ NONLINEAR EVOLUTION
- NEW PHASE OF QCD MATTER ⇒ COLOR GLASS CONDENSATE
- TRANSITION HAPPENS AT LOW $x$, HIGH $A$
HIGH-DENSITY QCD: SATURATION

- $F_2$ AND $F_L$ SEPARATELY DEPEND ON GLUON & ON EVOLUTION MECHANISM
  $\Rightarrow$ MEASURING BOTH PINS DOWN GLUON & EVOLUTION

- WHERE AND HOW IS ALTARELLI-PARISI RISE QUENCHED?

- UNDERSTANDING OF NON-LINEAR QCD REGIME STILL TENTATIVE

- MODELS/THEORIES CAN BE TESTED & DISENTANGLED
HIGH-DENSITY QCD: DIFFRACTION

- DIFFRACTION PROBES FACTORIZATION & PERTURBATIVE-NONPERTURBATIVE INTERFACE
- ENHANCED GLUON SENSITIVITY
- ACCESS TO TRANSVERSE DEGREES OF FREEDOM
CONCLUSION
SUMMARY

• The main impact of the LHeC is PDF+$\alpha_s$ uncertainties at 1% or below.

• The LHeC is a top-Higgs factory with the potential of very clean measurements in specific channels.

• The LHeC is the mecca of high-density QCD.