APCTP Workshop for Particle Physics Phenomenology [Nov.13(Fri)-15(Sun),2020] Higgs physics with electron-proton colliders

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w/ Adil Jueid, Jin Heung Kim, Soojin Lee 2020. 11.14.

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## **Future colliders**

- Hadron colliders
  - High luminosity LHC (HL-LHC);
  - High energy LHC (HE-LHC);
  - Future Circular Collider for hadrons (FCC-hh);
- Electron-positron colliders
  - International Linear Collider (ILC);
  - Compact Linear Collider (CLIC);
  - Future Circular Collider for electrons and positrons (FCC-ee);
  - Chinese Electron-Positron Collider (CEPC).
- Electron-hadron colliders
  - HL-LHeC, HE-LHeC, and FCC-eh.

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# 1. Deep Inelastic Scattering and HERA

- In 1955
  - Scattering of the electron off proton with  $E_e = 0.2 \text{ GeV}$
  - Finite proton radius of  $\simeq 0.74\,{\rm fm}.$
- SLAC-MIT experiment in 1968
  - $-E_e=10~{
    m GeV}$
  - Proton structure function  $F_2(x, Q^2)$  at fixed Bjorken x as a function of  $Q^2$  was measured.
  - partons!
- SLAC in 1978

 $\implies$ 

– Polarization asymmetry in  $e^-p$  scattering

– RH weak isospin charged of the electron is zero.

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 $0.2 \,\,\mathrm{GeV}$ 

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### First electron-proton collider

### HERA (construction from 1984 to 1992)





# H1 and ZEUS: two collider experiments in operation since 1992 for 15 years.

- A unique lepton proton collider
- $E_e = 27.5 \,\, {
  m GeV}, \ \ E_p = 920 \,\, {
  m GeV} \Longrightarrow \sqrt{s} \simeq 0.3 \,\, {
  m TeV}$
- Physics data taking: 1992-2007
- HERA I
  - -1992-2000
  - unpolarized lepton beams, mainly with  $e^+$ .
- HERA II
  - -2003-2007
  - the luminosity was increased
  - polarized  $e^{\pm}$  data were taken with about equal amounts in terms of charge and polarization states.



# Main results of HERA

- Structure Functions and Parton Distributions
- QCD: Measurements of  $\alpha_s$  in Inclusive DIS
- Jet Measurements
- Heavy Flavors
- Electroweak Measurements: CC vs. NC
- New physics Searches: leptoquarks

# Next ep collider design?

- the need for higher energy
- the need for much higher luminosity

# Next ep collider design?

- the need for higher energy
- the need for much higher luminosity

# LHeC: the most feasible!



## First CDR in 2012

CERN-OPEN-2012-015 LHeC-Note-2012-002 GEN Geneva, June 13, 2012





#### A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group



### **Allowing some options**

- $E_p = 7$  TeV and  $E_e = 60 140$  GeV
- design luminosity  $10^{33}/\text{cm}^2/\text{s}$
- The electron accelerator? LHeC either as a ring-ring or as a linac-ring collider.

- Two electron beam accelerator designs
  - RR option: a ring mounted on top of the LHC;
  - LR option: Energy Recovery Linac in a racetrack configuration;
- LHeC is designed to run simultaneously with *pp* at the HL-LHC.
- LR option was favored.

### **Electron accelerator**



- Default LHeC racetrack configuration.
- Each linac accelerates the beam to 10 GeV.
- After 3 passes, we have 60 GeV electron energy.

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### **Asymmetric detector!**



### We can distinguish forward from backward

#### 2012 CDR

parameter [unit]	LH	IeC			
species	e <sup>-</sup>	$p, {}^{208}\mathrm{Pb}^{82+}$			
beam energy (/nucleon) [GeV]	60	7000, 2760			
bunch spacing [ns]	25,100	25, 100			
bunch intensity (nucleon) $[10^{10}]$	$0.1 \ (0.2), \ 0.4$	17 (22), 2.5			
beam current [mA]	6.4(12.8)	860 (1110), 6			
rms bunch length [mm]	0.6	75.5			
polarization $[\%]$	90	none, none			
normalized rms emittance $[\mu m]$	50	3.75(2.0), 1.5			
geometric rms emittance [nm]	0.43	$0.50 \ (0.31)$			
IP beta function $\beta_{x,y}^*$ [m]	$0.12 \ (0.032)$	$0.1 \ (0.05)$			
IP spot size $[\mu m]$	7.2 (3.7)	7.2(3.7)			
synchrotron tune $Q_s$		$1.9 \times 10^{-3}$			
hadron beam-beam parameter	0.0001	(0.0002)			
lepton disruption parameter $D$	6 (	(30)			
crossing angle	0 (detector-int	egrated dipole)			
hourglass reduction factor $H_{hg}$	0.91 (0.67)				
pinch enhancement factor $H_D$	1.35				
CM energy [TeV]	1300, 810				
luminosity / nucleon $[10^{33} \text{ cm}^{-2} \text{s}^{-1}]$	1 (10), 0.2				



CERN-ACC-Note-2020-0002 Geneva, July 28, 2020





#### The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group



# **Cost saving**

Component	$\begin{array}{c} {\rm CDR} \ 2012 \\ {\rm (60GeV)} \end{array}$	Stage 1 (30 GeV)	Default (50 GeV)
SRF System	805	402	670
SRF R+D and Prototyping	31	31	31
Injector	40	40	40
Arc Magnets and Vacuum	215	103	103
SC IR Magnets	105	105	105
Source and Dump System	5	5	5
Cryogenic Infrastructure	100	41	69
General Infrastructure and Installation	69	58	58
Civil Engineering	386	289	289
Total Cost	1756	1075	1371

Parameter	Unit	LHeC option						
		1/3 LHC	1/4 LHC	1/5 LHC	1/6 LHC			
Circumference	m	9000	6750	5332	4500			
Arc radius	m · $2\pi$	1058	737	536	427			
Linac length	${ m m}\cdot 2$	1025	909	829	758			
Spreader and recombiner length	$m \cdot 4$	76	76	76	76			
Electron energy	$\mathrm{GeV}$	61.1	54.2	49.1	45.2			

c.m. energy

**1.3 TeV** 

1.19 TeV



### LHC schedule

# LS2 Report: A new schedule

As a result of the shutdown caused by the COVID-19 crisis, the injectors will restart at the end of the year and the LHC will restart in autumn 2021

24 JUNE, 2020	By Anaïs Schaeffer
---------------	--------------------

	2019	2019 2020 2021		1		2022 2023			2024 2025			2026 20		202	027														
JF№	1AMJJASON	NDJ FMAM	JJASON	JFMA	MJJA	SOND	JFM	AMJ	JASON	DJF	MAM	JJASC	ND	JFM	AMJJ	JASO	NDJ	FM	AMJJ	ASON	DJF	FMA	MJJA	ASO	ND	JFMA	(M)	AS	OND
																			Ш										
	Long Sh	utdown	2 (LS2)							Run	3								L	ong S	Shu	tdo	wn 3	3 (L	_S3	)			

2028	2029	2030	2031	2032	2033	2034	2035	2036	
JFMAMJJASONDJFM	MAMJJASOND	JFMAMJJASOND							
	Run 4		LS4		Run 5		LS5		

### Schedule

Parameter	Unit		]	LHeC		FCC	C-eh
		CDR	Run 5	Run 6	Dedicated	$E_p=20\mathrm{TeV}$	$E_p = 50 \mathrm{TeV}$
$E_e$	${ m GeV}$	60	30	50	50	60	60
$N_p$	$10^{11}$	1.7	2.2	2.2	2.2	1	1
$\epsilon_p$	$\mu { m m}$	3.7	2.5	2.5	2.5	2.2	2.2
$I_e$	$\mathrm{mA}$	6.4	15	20	50	20	20
$N_e$	$10^{9}$	1	2.3	3.1	7.8	3.1	3.1
$eta^*$	cm	10	10	7	7	12	15
Luminosity	$10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	1	5	9	23	8	15
			W	LHC			

a final, dedicated, stand-alone ep phase

# 3. Advantages of the LHeC over the LHC: no gluon-gluon fusion

**3. Advantages of the LHeC over the LHC** 

# 3-1. Small signal but much smaller backgrounds



#### LHC: single W production

q $\searrow$  $\overline{q}$ 

 $\sigma(pp 
ightarrow W^{\pm}) \simeq 10^5 \; {
m pb}$ 

#### LHC: single W production



$ ightarrow W^{\pm}) \simeq 10^5 ~{ m pb}$
$\sim 5 imes 10^{-5}$
$E_e = 50 \text{GeV},  E_p = 7 \text{TeV}$ $p_T^e > 10 \text{GeV}$
$1.00\mathrm{pb}$
$0.930\mathrm{pb}$
$0.796\mathrm{pb}$
$0.412\mathrm{pb}$
$0.177\mathrm{pb}$

 $e^- p \rightarrow e^- W^+ j, \quad e^- p \rightarrow e^- W^- j,$ 

 $e^- p \rightarrow \nu_e^- W^- j, \quad e^- p \rightarrow \nu_e^- Z j$ 

$$e^-p \to e^-Zj,$$

LHeC: only through VBF



Single top production at ep colliders



1.89 pb at the LHeC

# LHeC is a single top and anti-top quark factory



At the LHC,  $\sigma(pp \to tX) \simeq 200 \text{ pb}$ 

#### top quark pair production at ep colliders



At the LHC,  $\sigma(pp \to t\bar{t}X) \simeq 900 \text{ pb}$ 

the largest part of the background in many BSM models.

#### Single top production at ep colliders

#### Sensitive to the FCNC in top quark decays



3. Advantages of the LHeC over the LHC

# 3-2. Practically no pileups

# For example HH AT THE LHC



<sup>IVI</sup>HH



#### • HL-LHC

- $-\sim 20\%$  larger cross section, but much more difficult environment!
- Higher PU  $\Longrightarrow$  lower sensitivity to  $\kappa_{\lambda}$  variations

### At LHeC, PU is only 0.1

# 4. What can we do with the LHeC?

# 4-1 PDF and QCD

- Parton Distributions Resolving the Substructure of the Proton
- Exploration of Quantum Chromodynamics
  - Determination of the strong coupling constant
  - Discovery of New Strong Interaction Dynamics at Small x

# **4-2 EW precision measurements**

Coupling	PDG	Expected uncertainties							
parameter	value	LHeC-60	LHeC-60 ( $\delta_{uncor.}=0.25\%$ )	LHeC-50					
$g^u_A$	$0.50  {}^{+0.04}_{-0.05}$	0.0022	0.0015	0.0035					
$g^d_A$	$-0.514 \begin{array}{c} +0.050 \\ -0.029 \end{array}$	0.0055	0.0034	0.0083					
$g_V^u$	$0.18\ {\pm}0.05$	0.0015	0.0010	0.0028					
$g_V^d$	$-0.35 \ ^{+0.05}_{-0.06}$	0.0046	0.0027	0.0067					



#### LHeC: Best for Anomalous Triple Gauge Couplings

$$\mathcal{L}_{TGC}/g_{WWV} = ig_{1,V}(W^{+}_{\mu\nu}W^{-}_{\mu\nu}V_{\nu} - W^{-}_{\mu\nu}W^{+}_{\mu}V_{\nu}) + i\kappa_{V}W^{+}_{\mu}W^{-}_{\nu}V_{\mu\nu} + \frac{i\lambda_{V}}{M_{W}^{2}}W^{+}_{\mu\nu}W^{-}_{\nu\rho}V_{\rho\mu} + g_{5}^{V}\epsilon_{\mu\nu\rho\sigma}(W^{+}_{\mu}\overleftrightarrow{\partial}_{\rho}W^{-}_{\nu})V_{\sigma} - g_{4}^{V}W^{+}_{\mu}W^{-}_{\nu}(\partial_{\mu}V_{\nu} + \partial_{\nu}V_{\mu}) + i\tilde{\kappa}_{V}W^{+}_{\mu}W^{-}_{\nu}\tilde{V}_{\mu\nu} + \frac{i\tilde{\lambda}_{V}}{M_{W}^{2}}W^{+}_{\lambda\mu}W^{-}_{\mu\nu}\tilde{V}_{\nu\lambda},$$

#### Direct W and Z Production: small but good enough

Process	$E_e = 50 \mathrm{GeV},  E_p = 7 \mathrm{TeV}$
	$p_T^e > 10 \mathrm{GeV}$
$e^-W^+j$	$1.00\mathrm{pb}$
$e^-W^-j$	$0.930\mathrm{pb}$
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# **4-3 Higgs physics**

- No gluon-gluon fusion
- VBF production is dominant!
- Separate NC from CC production
- Higgs couplings with high precision





#### No cuts

		10% h accontanco
The integrated Inuminosity	Bounds of the $\kappa_{\lambda}$	iv /o ii acceptance
$\mathcal{L} = 1 \text{ ab}^{-1}$	[-0.63, 4.61]	[-2.65, 6.62]
$\mathcal{L} = 2 \text{ ab}^{-1}$	[-0.28, 4.25]	[-1.95, 5.93]
$\mathcal{L} = 3 \text{ ab}^{-1}$	[-0.11, 4.08]	[-1.59, 5.57]

Results can be significantly improved. Sensitivity will help the HL-LHC:  $0 \times 1 \times 1 \times 1$ 

 $0.5 < k_{\rm v} < 1.5$ 

#### Total cross sections, in fb, for inclusive Higgs production

Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
$\frac{E_p}{\sqrt{s}}$	$\begin{array}{c} {\rm TeV} \\ {\rm TeV} \end{array}$	$7\\1.30$	$\begin{array}{c} 13.5 \\ 1.77 \end{array}$	$\begin{array}{c} 20\\ 2.2 \end{array}$	$50\\3.46$
$\sigma_{CC} \ (P = -0.8)$	fb	197	372	516	1038
$\sigma_{NC} \ (P = -0.8)$	fb	24	48	70	149
$\sigma_{CC} \ (P=0)$	fb	110	206	289	577
$\sigma_{NC} \ (P=0)$	fb	20	41	64	127
HH in CC	fb	0.02	0.07	0.13	0.46





# Charm tagging at the LHC

- CMS: MVA–based discriminator PAS BTV-16-001
  - displaced tracks
  - secondary vertices
  - soft leptons

- ATLAS: ATL-PHYS-PUB-2015-001
  - impact parameter
  - secondary-vertex (reconstruct b to c decay vertex)
  - calibration multi-jet events with reconstructed D mesons, t-tbar pairs

#### Tagging efficiency is too small at the LHC.

# $Charm{}_{1}tagging{}_{2}at the LHeC_{2}$

C-jet efficiency vs light-jet efficincy



Significant improvement in charm jet tagging efficiency from 23-24% for a R = 0.9 to 30% using R = 0.5 anti-kt jets and half nominal vertex resolution at light jet tagging efficiency 5%.

0.2

• Precision of coupling constants are estimated to be

Hbb: 0.5%
Hcc: 4%

assuming 1 ab-1 at LHeC. (Statistics error only.)
 Big potential for measurements of Higgs coupling.

# 4-4 BSM at the LHeC

- Leptoquarks
- Charged Higgs
- SUSY
- Triple Gauge Couplings
- Axion-Like Particles

- Vector-Like Quarks
- heavy fermions, neutrinos
- Charged Higgs
- Neutral heavy higgs
- long-lived particles
- dark photons

# Georgi-Machacek model

• Extended Higgs sector, with isospin triplets, satisfying the custodial symmetry at tree level

$$ho = rac{m_W^2}{m_Z^2\cos heta_W} = 1$$

- Higgs bidoublet and two triplets (one real and one complex) arranged as a bitriplet
- physical spectrum includes fiveplet without couplings to fermions.

$$H_5^{++}, \hspace{0.2cm} H_5^+, \hspace{0.2cm} H_5^0, \hspace{0.2cm} H_5^-, \hspace{0.2cm} H_5^{--}.$$

• only produced by VBF

G.A., H. Sun and K. Wang, arXiv:1712.07505



The significance contour bands in the plane of production cross section times branching ratio

# 7. Conclusions

- LHeC is an energy frontier collider.
- Ordinary QCD physics shall be precise probed.
- Higgs physics has a new window.
- Some BSM models can be also probed.