Energy Frontier Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics

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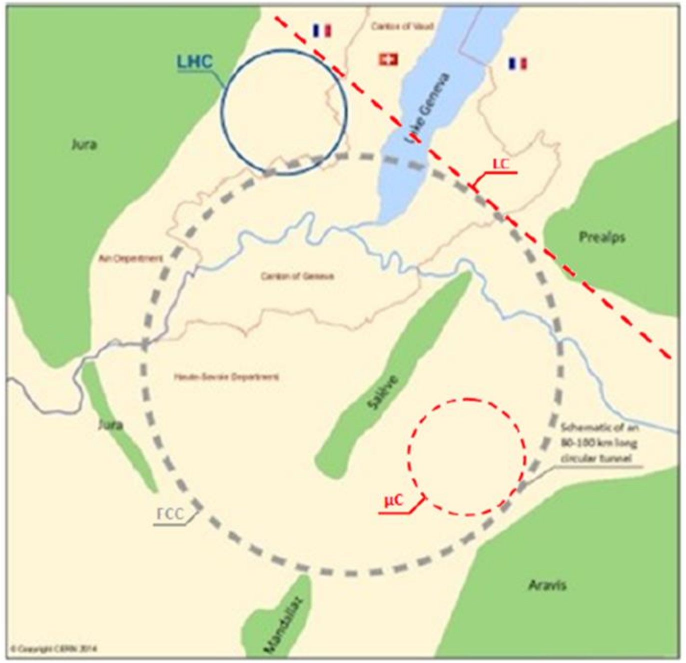
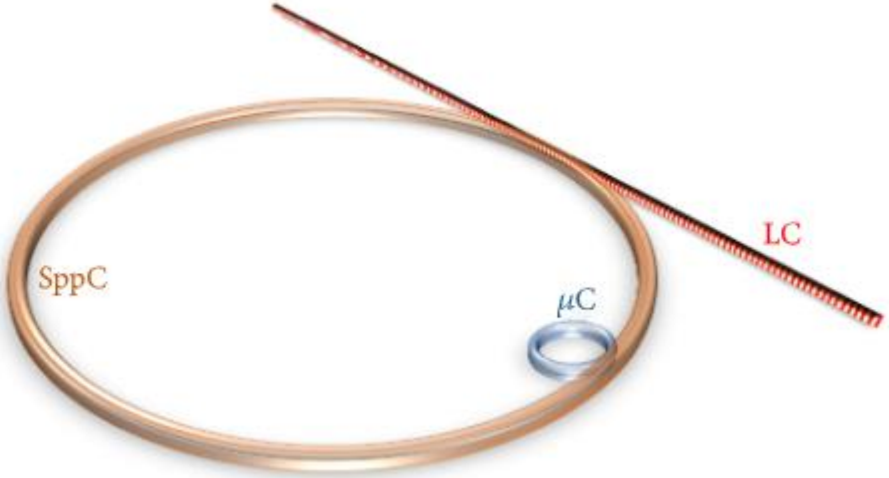
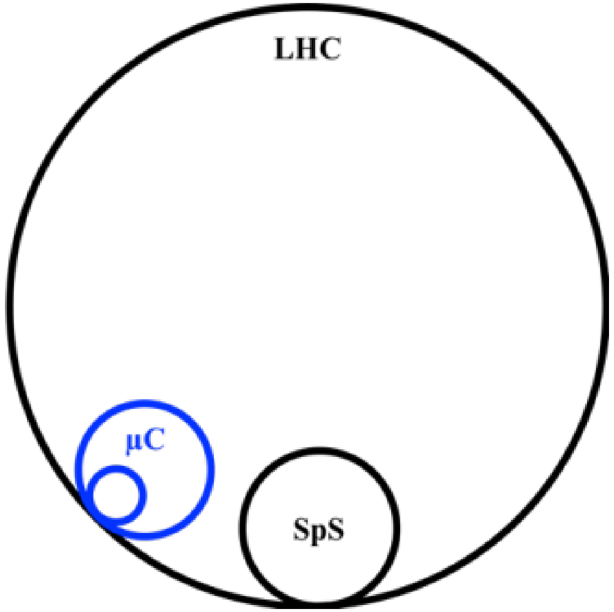
ATLAS, LHeC and FCC Collaborations, CERN
Member of Plenary ECFA (Jan 2019 – Jul 2020)



Nucl. Instrum. and Meth., A 871 (2017) 47-53



Advances in High Energy Physics (2017) 4021493



e-Print: 1905.05564 [physics.acc-ph]

ABSTRACT

Construction of **linear collider** (or **dedicated e-linac**) or **muon collider** (or **dedicated μ-ring**) **tangential to energy frontier hadron colliders** will give opportunity to investigate **lepton-hadron and photon-hadron interactions at tens-TeV center-of-mass energies.**

These lepton-hadron and photon-hadron colliders will **essentially enlarge physics search potential of the hadron collider's** host laboratory both in SM and BSM phenomena.

In this presentation main parameters of the **LHC/FCC/SppC based ep, eA, μp, μA, γp and γA colliders** will be discussed, together with their physics search potential.

Certainly, these machines have **great potential for clarifying QCD basics.**

Concerning **BSM physics** search, their **potential exceeds that of corresponding lepton colliders** essentially and is **comparable (and complementary) with** the potential **of basic hadron colliders**.

Content

1. Introduction

20 years ago the Standard Model had **two experimental missing's**:

- Higgs mechanism in electroweak part
- Confinement hypothesis in QCD part

Electroweak part was completed by discovery of the Higgs boson at the LHC.

QCD part is still uncompleted, Confinement should be clarified.

Two regions are crucial:

- **Bjorken x close to 1**, will be investigated at EIC,
- **Small x (<<10^{-4}) at high Q^2 (>>10^2 GeV ^{2}),** will be investigated at LHeC and energy frontier lh/γh colliders.

In addition, LHeC and energy frontier lh/γh colliders will **provide pdf's for adequate interpretation of HE-LHC, FCC and SppC data.**

Concerning **BSM physics**, it should be mentioned that **potential of lh/γh colliders:**

- **essentially exceeds** that of corresponding **lepton colliders**
- is **comparable with** (and complementary to) potential of corresponding **hadron colliders**.

Table 1. Future Energy Frontier Colliders: colliding beams vs collider types

	Ring-Ring	Linear	Linac-Ring
pp, pA, AA	HE-LHC, FCC, SppC	-	-
ee, γe, γγ	-	ILC, CLIC, PWFA-LC	-
ep, eA	-	-	**LHeC, FCC/SppC based**
γp, γA	-	-	**HE-LHC/FCC/SppC based**
μμ	μC	-	-
μp, μA	**LHC/FCC/SppC based**	-	-

Classification of colliders

ECFA presentation 25.11.2010, CERN

1. Colliding particles
   - hadrons
   - leptons
   - lepton-hadron

2. Collider schemes
   - ring-ring
   - linear
   - linac-ring

The ring-ring colliders are the most advanced ones from technology point of view and are widely used around the (developed) world.

The linear (linac-linac) colliders are less familiar; however, a lot of experience is gained through Standard Linear Collider (SLC) operation and ILC/CLIC related workout.

The linac-ring colliders require more R&D.

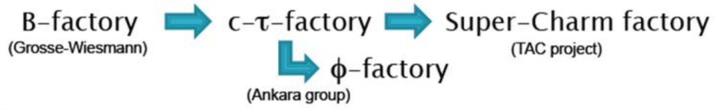
S. SULTANSOY 25.11.2010 CERN 4

Linac-ring type colliders: two directions*

Lepton-hadron and photon-hadron colliders:

→ ILC+FCC/SppC → PWFA+FCC/SppC

Factories:



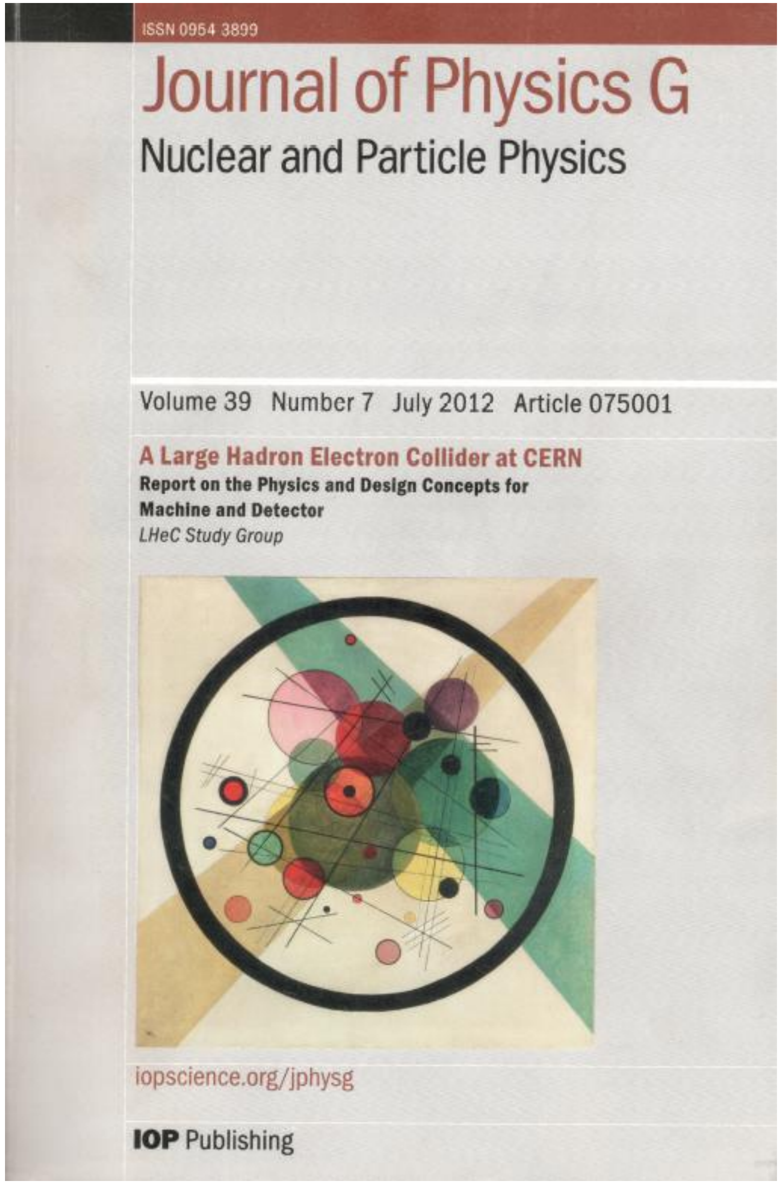
+ HL/HE-LHC based μh

+ FCC/SppC based μh

* For details and ref's see: A. Akay, H. Karadeniz and S. Sultansoy, Review of Linac-Ring-Type Collider Proposals, Int. J. Mod. Phys. A 25 (2010) 4589

S. SULTANSOY 25.11.2010 CERN 5

2. LHeC: 60 GeV ERL


ISSN 0954 3899

Journal of Physics G

Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

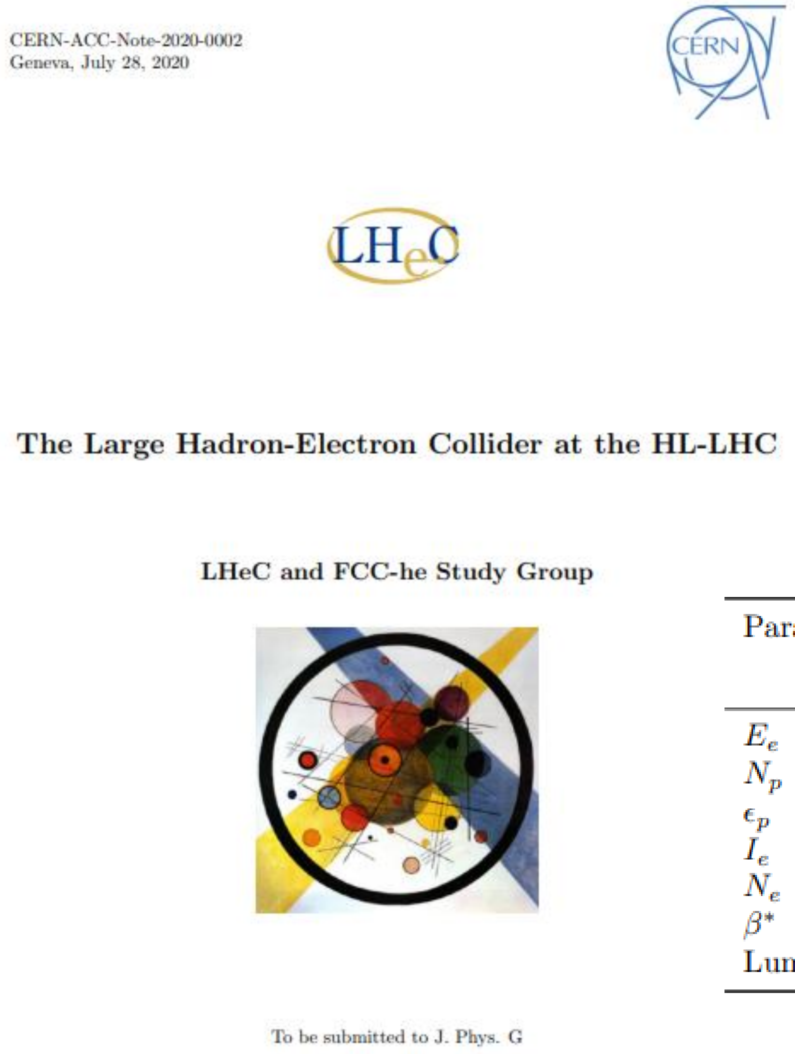
A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing

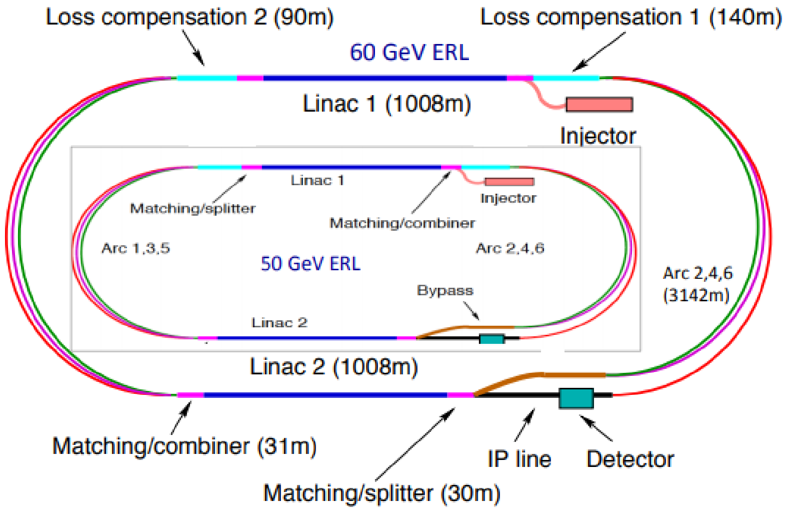

CERN-ACC-Note-2020-0002

Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

To be submitted to J. Phys. G



Parameter	Unit	LHeC			
		CDR	Run 5	Run 6	Dedicated
E_e	GeV	60	30	50	50
N_p	10^{11}	1.7	2.2	2.2	2.2
ϵ_p	μm	3.7	2.5	2.5	2.5
I_e	mA	6.4	15	20	50
N_e	10^9	1	2.3	3.1	7.8
β^*	cm	10	10	7	7
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23

3. LHeC: Alternative Scenarios

Süleyman Demirel Üniversitesi Fen Edebiyat Fakültesi Fen Dergisi
Süleyman Demirel University Faculty of Arts and Sciences Journal of Science
2018, 13(2): 173-178
DOI: 10.29233/sdufeffd.468814

The LHeC Project: e-Ring Revisited

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(Alınış / Received: 09.10.2018, Kabul / Accepted: 26.11.2018, Yayımlanma / Published: 30.11.2018)

Abstract: Construction of a new 9 km long e-ring tangential to the Large Hadron Collider (LHC) has been proposed as an option for QCD-Explorer stage of the Large Hadron electron Collider (LHeC). It is shown that $L=10^{33}$ cm^{-2}s^{-1} can be achieved with 90 MW synchrotron radiation losses. This luminosity value, which coincides with basic version of ERL60⊗LHC, will be sufficient for precise determination of (Parton Distribution Function) PDFs for LHC, as well as exploration of QCD basics, especially small x Björken region up to 10^{-6} at $Q^2 \approx 1$ GeV^2. In addition, some comments on basic and upgraded versions of ERL60⊗LHC are presented as well. It is shown that upgraded ERL60⊗LHC version with $L=10^{34}$ cm^{-2}s^{-1} requires high wall plug power exceeding 160 MW.

Next stage: 9 km e-ring → μ-ring with E_μ = 3 TeV

√S : 1.3 TeV → 9.1 TeV

Another alternative, namely, one-pass linac will give opportunity to upgrade electron beam energy, if necessary! + γp and γA options!

Table 3. Collider Parameters of LHeC's ERL60⊗LHC option with $L=10^{34}$ cm^{-2}s^{-1}

Parameter [Unit]	Protons	Electrons
Beam energy [GeV]	7000	60
Normalized emittance, $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta function @ IP, $\beta^*_{x,y}$ [m]	0.05	0.1
RMS beam sizes @ IP, $\sigma^*_{x,y}$ [μm]	4	4
Bunch length, σ_z [mm]	75	10
Beam current [mA]	1112	25
Bunch spacing [ns]	25	25
Bunch population	2.2×10^{11}	4×10^9

Wall plug power is over 160 MW !

Fig. 1. Bird's eye view of proposed ring-ring option for LHeC

4. Energy Frontiers

FCC based ep, γp, μp, eA, γA, μA, FEL γA colliders

Nuclear Inst. and Methods in Physics Research, A 871 (2017) 47–53

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ELSEVIER

Future circular collider based lepton–hadron and photon–hadron colliders: Luminosity and physics

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A B S T R A C T

Construction of future electron–positron colliders (or dedicated electron linac) and muon colliders (or dedicated muon ring) tangential to Future Circular Collider (FCC) will give opportunity to utilize highest energy proton and nucleus beams for lepton–hadron and photon–hadron collisions. Luminosity values of FCC based ep, μp, eA, μA, γp and γA colliders are estimated. Multi-TeV center of mass energy ep colliders based on the FCC and linear colliders (LC) are considered in detail. Parameters of upgraded versions of the FCC proton beam are determined to optimize luminosity of electron–proton collisions keeping beam–beam effects in mind. Numerical calculations are performed using a currently being developed collision point simulator. It is shown that $L_{ep} \sim 10^{32}$ cm^{-2} s^{-1} can be achieved with LHeC-like upgrade of the FCC parameters. Moreover, "dynamic focusing" scheme could provide opportunity to handle $L_{ep} \gtrsim 10^{33}$ cm^{-2} s^{-1}.

Table 5
Main parameters of ILC ⊗ FCC based ep collider corresponding to the disruption value $D_e = 25$.

E_e (GeV)	$\sqrt{s}$ (TeV)	$N_p(10^{11})$	L_{ep} (cm^{-2} s^{-1})	ξ_p
250	7.08	2.3	57×10^{30}	1.09×10^{-3}
500	10.0	4.6	149×10^{30}	9.40×10^{-4}

Table 8
Main parameters of PWFA-LC ⊗ FCC based ep collider corresponding to the disruption value $D_e = 25$. IBS growth times are given for collision energy $E_p = 50$ TeV and injection energy $E_p = 3.3$ TeV.

E_e (GeV)	$\sqrt{s}$ (TeV)	$N_p(10^{11})$	L_{ep} (cm^{-2} s^{-1})	ξ_p	$\tau_{IBS,x}$ (h)	
					Injection	Collision
125	5.00	1.15	65.0×10^{30}	5.47×10^{-4}	171	63
250	7.08	2.30	86.0×10^{30}	5.47×10^{-4}	85	31
500	10.0	4.60	129×10^{30}	5.47×10^{-4}	43	16
1500	17.3	13.8	258×10^{30}	5.47×10^{-4}	14	5.2
5000	31.6	45.8	433×10^{30}	5.47×10^{-4}	4	1.5

Table 10
Main parameters of the FCC based μp colliders.

Collider name	$\sqrt{s}$, TeV	$L_{\mu p}$, cm^{-2} s^{-1} (Avg.)	ξ_p	ξ_μ
μ63-FCC	3.50	0.20×10^{31}	1.8×10^{-3}	5.4×10^{-4}
μ750-FCC	12.2	49×10^{31}	1.1×10^{-1}	3.3×10^{-3}
μ1500-FCC	17.3	43×10^{31}	1.1×10^{-1}	8.3×10^{-4}

Table 13
Main parameters of μC ⊗ FCC based μ-Pb colliders.

Collider name	E_μ, TeV	Nominal parameters		
		$L_{\mu Pb}$, cm^{-2} s^{-1} (Avg.)	ξ_{Pb}	ξ_μ
μ63-FCC	0.063	1.1×10^{31}	0.1	1.5×10^{-1}
μ750-FCC	0.75	1.3×10^{31}	12	7.3×10^{-3}
μ1500-FCC	1.5	1.1×10^{31}	47	1.8×10^{-3}
		Upgraded parameters		

4. Energy Frontiers

FCC based ep, γp, μp, eA, γA, μA, FEL γA colliders

Y.C. Acar et al. Nuclear Inst. and Methods in Physics Research, A 871 (2017) 47–53

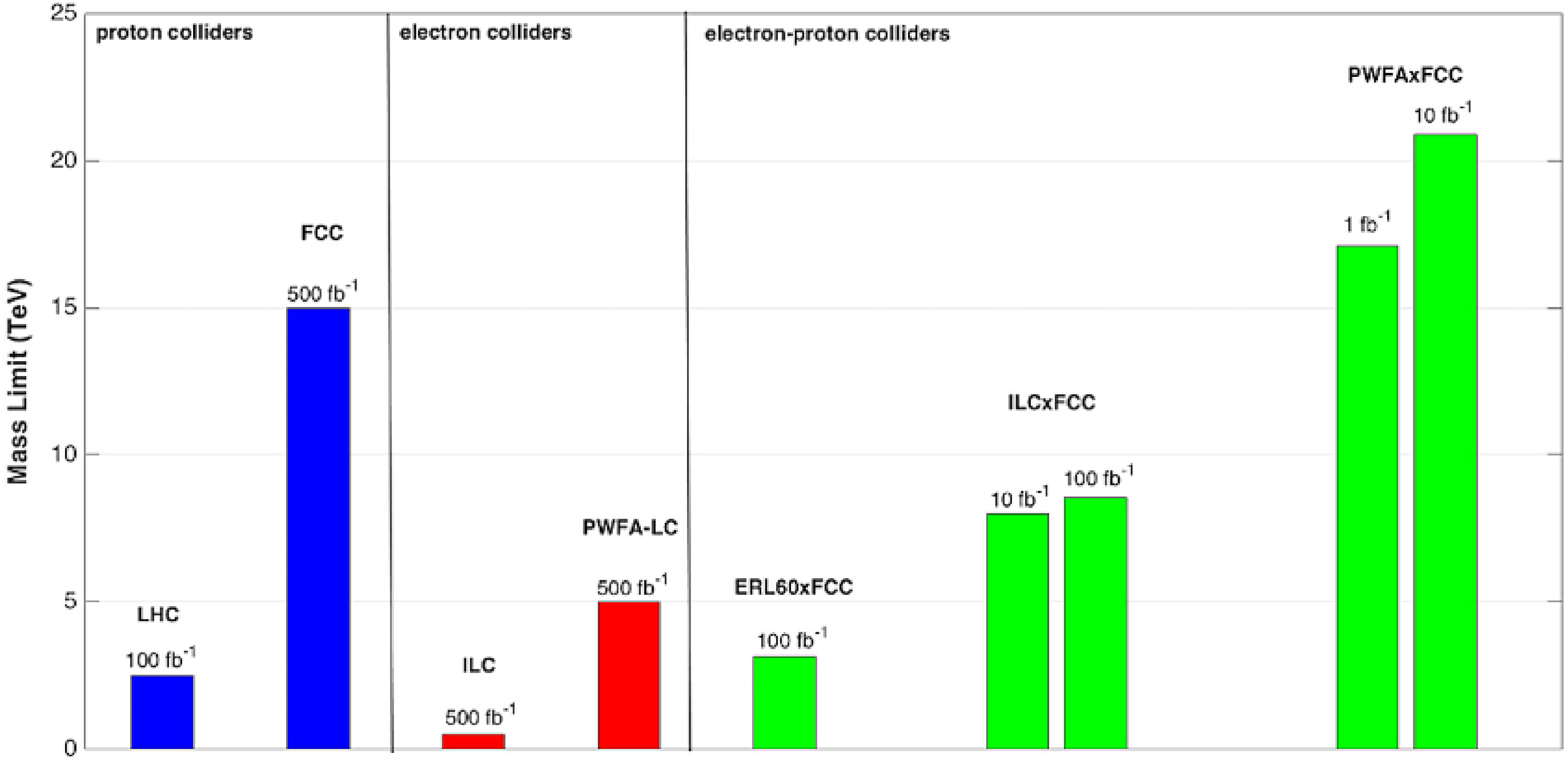

Fig. 2. Discovery limits for color octet electron at different pp, e^+e^- and ep colliders [46]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Energy Frontiers

SppC based ep and μp colliders

Hindawi
Advances in High Energy Physics
Volume 2017, Article ID 4021493, 6 pages
https://doi.org/10.1155/2017/4021493

Hindawi

Research Article

SppC Based Energy Frontier Lepton-Proton Colliders: Luminosity and Physics

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Main parameters of Super proton-proton Collider (SppC) based lepton-proton colliders are estimated. For electron beam parameters, highest energy International Linear Collider (ILC) and Plasma Wake Field Accelerator-Linear Collider (PWFA-LC) options are taken into account. For muon beams, 1.5 TeV and 3 TeV center of mass energy muon collider parameters are used. In addition, ultimate μp collider which assumes construction of additional 50 TeV muon ring in the SppC tunnel is considered. It is shown that luminosity values exceeding $10^{32}\ \text{cm}^{-2}\,\text{s}^{-1}$ can be achieved with moderate upgrade of the SppC proton beam parameters. Physics search potential of proposed lepton-proton colliders is illustrated by considering small Björken x region as an example of SM physics and resonant production of color octet leptons as an example of BSM physics.

Table 6: Main parameters of SppC based μp colliders.

E_μ, TeV	E_p, TeV	$\sqrt{S}$, TeV	$L_{\mu p}$, cm^{-2} s^{-1}	ξ_μ	ξ_p
0.75	35.6	10.33	5.5×10^{32}	8.7×10^{-3}	6.0×10^{-2}
0.75	68	14.28	12.5×10^{32}	8.7×10^{-3}	8.0×10^{-2}
1.5	35.6	14.61	4.9×10^{32}	8.7×10^{-3}	6.0×10^{-2}
1.5	68	20.2	42.8×10^{32}	8.7×10^{-3}	8.0×10^{-2}

3.1. Small Björken x. As mentioned above, investigation of extremely small x region ($x < 10^{-5}$) at sufficiently large Q^2 (>10 GeV^2), where saturation of parton density should manifest itself, is crucial for understanding of QCD basics. Smallest achievable x at lp colliders is given by Q^2/S. For LHeC with $\sqrt{s} = 1.3$ TeV minimal achievable value is $x = 6\times10^{-6}$. In Table 9, we present smallest x values for different SppC based lepton-proton colliders (E_p is chosen as 68 TeV). It is seen that proposed machines has great potential for enlightening of QCD basics.

Table 9: Attainable Björken x values at $Q^2 = 10\ \text{GeV}^2$.

E_l (TeV)	0.5	5	1.5	50
x	7×10^{-8}	7×10^{-9}	2×10^{-8}	7×10^{-10}

4. Energy Frontiers
SppC based ep and μp colliders

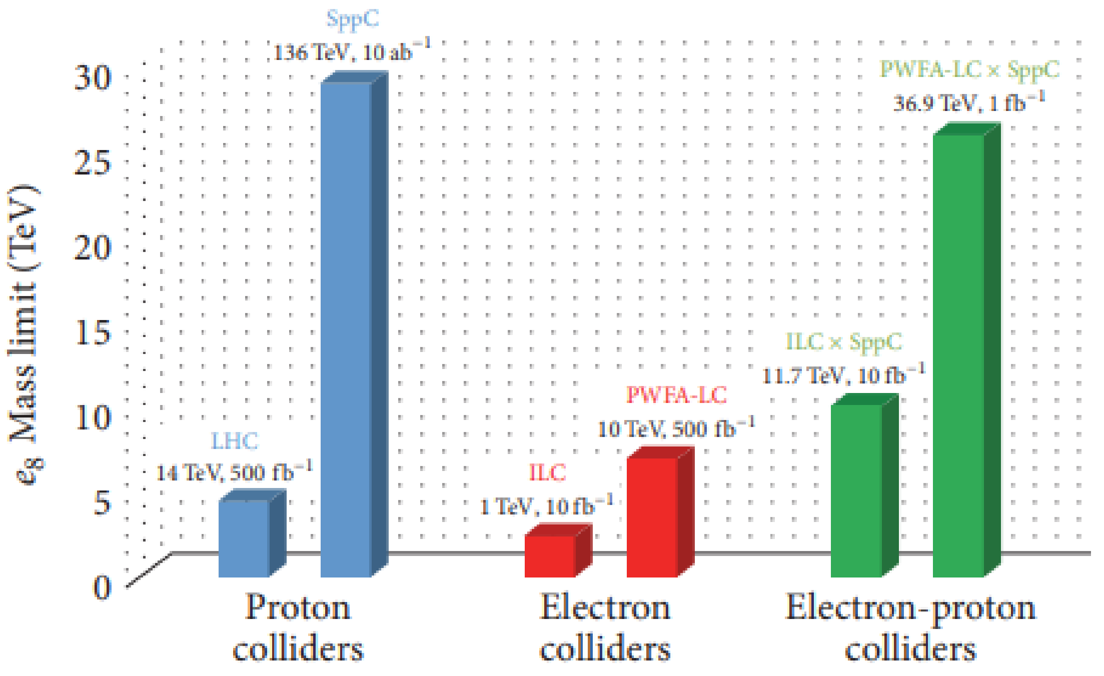


FIGURE 2: Discovery mass limits for color octet electron at different pp, e^+e^-, and ep colliders.

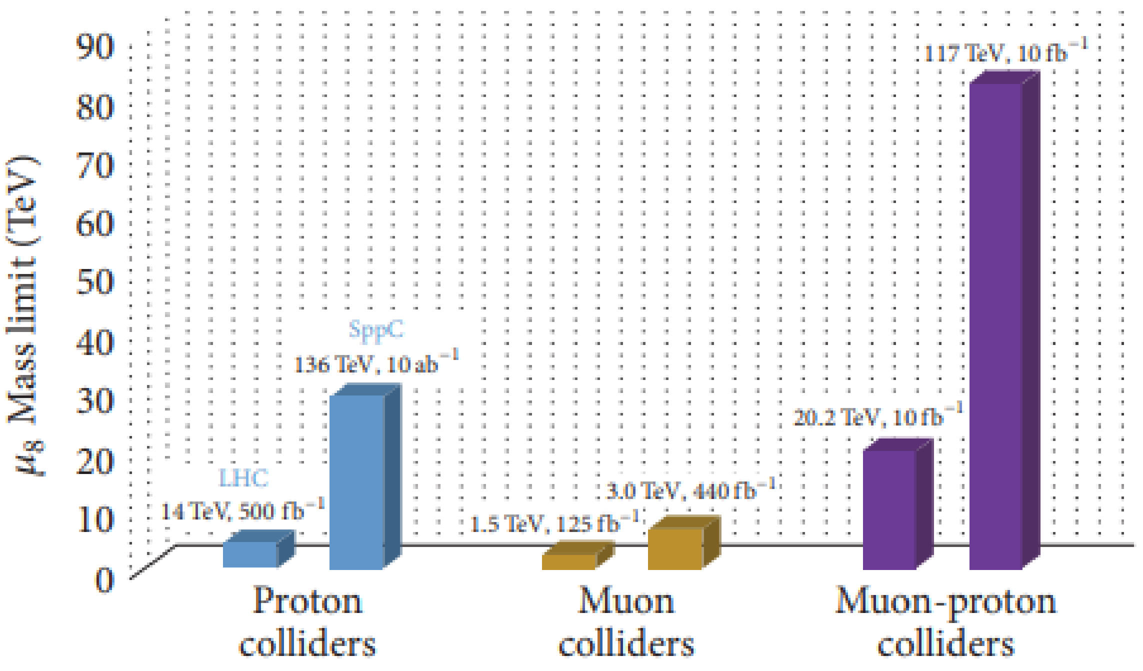
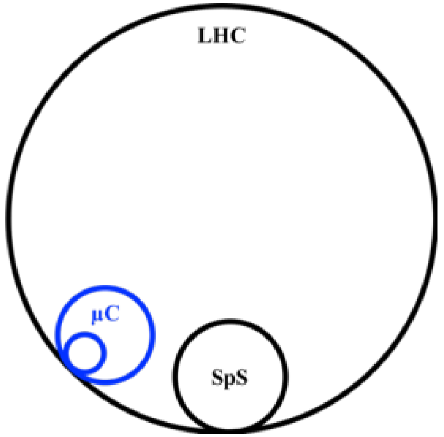


FIGURE 3: Discovery mass limits for color octet muon at different pp, $\mu^+\mu^-$, and μp colliders.

4. Energy Frontiers
HL/HE-LHC based μp colliders



Main parameters of HL-LHC and HE-LHC based *μp* colliders

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[c]ANAS Institute of Physics, Baku, Azerbaijan
[d]CERN, Geneva, Switzerland

Abstract

Construction of future Muon Collider tangential to the Large Hadron Collider will give opportunity to realize *μp* collisions at multi-TeV center of mass energies. Using nominal parameters of high luminosity and high energy upgrades of the LHC, as well as design parameters of muon colliders, it is shown that $L_{\mu p}$ of order of 10^{33} $cm^{-2}s^{-1}$ is achievable for different options with $\sqrt{s_{\mu p}}$ from 4.58 TeV to 12.7 TeV. Certainly, proposed *μp* colliders have huge potential for clarifying QCD basics and new physics search.

Keywords: LHC; Muon collider, *μp* colliders, Luminosity, QCD basics, New physics.

https://arxiv.org/ftp/arxiv/papers/1905/1905.05564.pdf

Table 7. Achievable *x* Björken values at the LHC based *μp* colliders.

√s, TeV	Q^2= 1 GeV²	Q^2= 25 GeV²
4.58	4.8×10^{-8}	1.2×10^{-6}
~ 6.4	2.5×10^{-8}	6.1×10^{-7}
~ 9	1.3×10^{-8}	3.1×10^{-7}
12.7	6.2×10^{-9}	1.6×10^{-7}

Table 4. Center of mass energies and luminosities of HL-LHC based *μp* colliders

E_μ, TeV	√s, TeV	L (nominal), 10^{33} $cm^{-2}s^{-1}$	L (upgraded), 10^{33} $cm^{-2}s^{-1}$
0.75	4.58	0.95	1.4
1.5	6.48	0.84	2.1
3	9.16	0.57	1.5

Table 5. Center of mass energies and luminosities of HE-LHC based *μp* colliders

E_μ, TeV	√s, TeV	L (nominal), 10^{33} $cm^{-2}s^{-1}$	L (upgraded), 10^{33} $cm^{-2}s^{-1}$
0.75	6.36	0.59	1.6
1.5	9	0.52	2.8
3	12.7	0.36	1.9

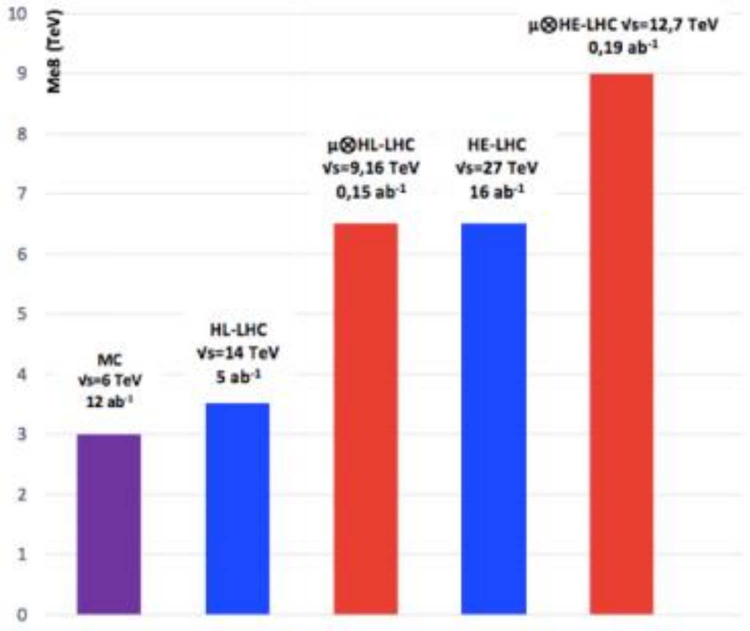


Figure 2. Discovery Limits for Color Octet Muon at the MC with √s=6 TeV, HL-LHC, HE-LHC and corresponding *μp* Colliders

5. QCD (not H) Explorer(s)

Higgs mechanism is responsible for 1% of mass of visible universe,

QCD is responsible for remaining 99% !!!

Luminosity vs energy in lepton-hadron collisions:

- **Higgs physics requires highest lumi,**
- **QCD basics requires highest energy.**

Modified **ERL60+LHC** with L = 10^{34} cm^{-2} s^{-1} requires **too much wall plug power**, while even this luminosity may not be sufficient for precision Higgs boson physics.

Let's leave the Higgs boson to the lepton and hadron colliders !

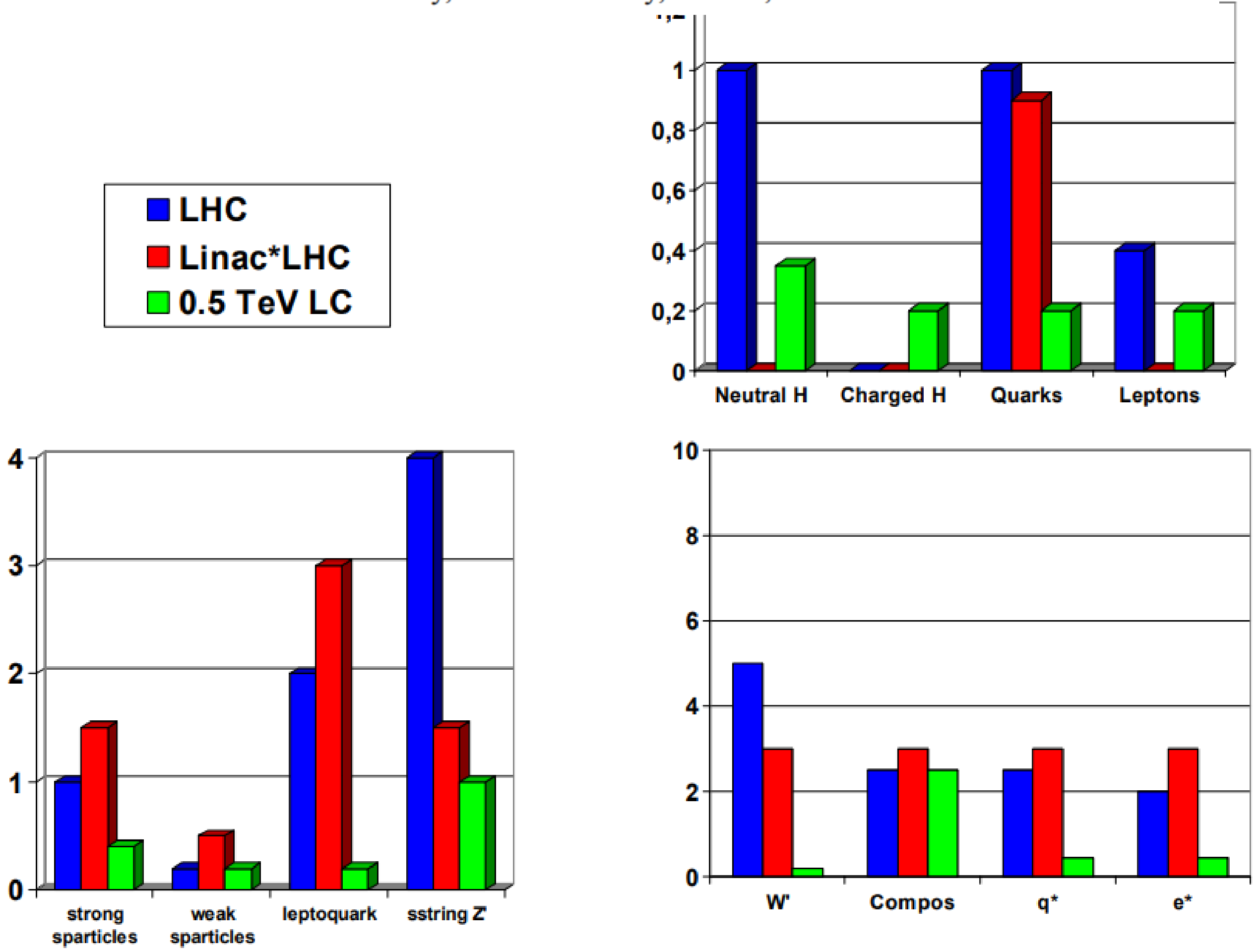
Clarifying of QCD basics (including confinement hypothesis) may lead to exceptional results (including cosmology and technology) !

6. BSM Physics

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

A REVIEW OF TEV SCALE LEPTON-HADRON AND PHOTON-HADRON COLLIDERS

S. Sultansoy, Gazi University, Ankara, TURKEY



https://accelconf.web.cern.ch/p05/PAPERS/TPAT098.PDF

See, also:

Mini-workshop on machine and physics aspects of CLIC based future collider options

F. Tecker (CERN)(ed.)

Sep, 2004

126 pages

Report number: CERN-OPEN-2004-004, CLIC-NOTE-613, CERN-CLIC-NOTE-613

http://cds.cern.ch/record/798726/files/open-2004-026.pdf

Table of Contents:

This figure played an important role in the initiation of the LHeC process.
It would be very useful to do similar work for the FCC based lp. (two examples are shown in slides 9 and 11)

7. Conclusion and recommendations

Obviously, **energy frontier lepton-hadron and photon-hadron colliders will essentially enlarge physics search potential of basic hadron colliders** for both the SM and BSM phenomena.

Therefore**, systematic study of accelerator, detector and physics search aspects** of the LHC/FCC/SppC based energy-frontier ep, γp, μp, eA, γA and μA colliders is necessary for long-range planning of HEP.

I invite the DIS community to start these studies. Your experience will allow to complete this work in a few years. This will be beneficial for next European Strategy document preparation.

Concerning linac-ring type colliders:

- energy recovery is mandatory for TAC Super-Charm Factory and EIC
- 60 GeV ERL may be considered as baseline (but not the sole) option for LHC ($E_p / E_e \approx 120$)
- 60 GeV ERL is not appropriate choice for FCC and SppC, since $\mathbf{E_p / E_e \approx 830}$!

Finally, **organization of special working group on the LHC/FCC based energy frontier lepton-hadron and photon-hadron colliders** (maximally disentangled from ERL60/PERLE governance) will be very useful. **It would be natural for DESY to take over this job.**

We have to create a table with collider types in columns, physics phenomena (particles, interactions, ...) in rows and fill in it.

8. Review articles

An Electron - proton collider in the TeV range

M. Tigner (Cornell U., LNS), B. Wiik (DESY), F. Willeke (DESY)

Nov 14, 1991

3 pages
Part of Proceedings, 1991 IEEE Particle Accelerator Conference (PAC 1991)
Published in: *Conf.Proc.C* 910506 (1991) 2910-2912, Particle Accel.Conf: IEEE 1991:2910-2912
Contribution to: IEEE 1991 Particle Accelerator Conference (APS Beam Physics)
Report number: CLNS-91-1079

IC/89/409

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

PROSPECTS OF THE FUTURE ep AND γp COLLIDERS: LUMINOSITY AND PHYSICS

S.F. Sultanov

Table II
Planned and possible ep colliders

Machine	$\sqrt{s}$ TeV	E_e TeV	E_p (TeV)	$n_e(10^{10})$	$n_p(10^{10})$	Coll. rate f(Hz)	$\mathcal{L}(10^{30}\ cm^{-2}s^{-1})$
Standard ep machines							
HERA	0.3	0.03	0.82	3.48	10	10^7	15
LHC+LEP I	1.3	0.05	8	8.2	30	5×10^6	200
LHC+LEP II	1.8	0.1	8	8.2	30	5×10^6	10
UNK + e–ring	0.6	0.03	3	-	-	-	100
SSC+e-ring	2.8	0.1	20	-	-	-	100
New type ep machines *							
UNK+VLEPP I	2.4	0.5	3	20	100	100	1 + 10
UNK+VLEPP II	3.5	1	3	20	100	100	1+10
UNK + VLEPP [1)]	4.9	2	3	20	100	100	1+10
LHC + CLIC [1)]	8	2	8	0.5	100	6×10^3	10+100
LHC+CLIC [2)]	4.8	0.7	8	0.6	100	10^4	10+100
SSC+LSC [1)]	28	10	20	0.08	100	8×10^4	100
LHC+e-linac [3)]	3	0.3	8	0.08	100	5×10^5	5×10^3
SSC+e-linac[3)]	8	0.8	20	0.05	100	5×10^5	10^4
Electron–proton linacs **							
VLEPP+p10	2	1	1	20	20	100	1+10
LSC+p10	10	5	5	0.08	0.08	8×10^4	100

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The post-HERA era: brief review of future lepton-hadron and photon-hadron colliders

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Abstract

Options for future *lp*, *lA*, *γp*, *γA* and FEL *γA* colliders are discussed.

CONTENTS

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Linac-Ring Type Colliders: Fourth Way To TeV Scale

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The present status of suggested linac-ring type *ep* and *γp* colliders is reviewed. The main parameters of these machines as well as e-nucleus and γ-nucleus colliders are considered. It is shown that sufficiently high luminosities may be achieved with a reasonable improvement of proton and electron beam parameters.

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International Workshop on Linac-Ring Type *ep* and *γp* Colliders

Four Ways to TeV Scale

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Abstract

Four known types of colliders, which may give an opportunity to achieve TeV center of mass energies in the near future (10-15 years), are discussed. Parameters of the linac-ring type *ep* and *γp* machines are roughly estimated. Some speculations on TeV scale physics are given. The physics goals of the TeV energy *ep* and *γp* colliders are considered.

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REVIEW OF LINAC–RING-TYPE COLLIDER PROPOSALS

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There are three possible types of particle colliders schemes: familiar (well-known) ring–ring colliders, less familiar but sufficiently advanced linear colliders, and less familiar and less advanced linac–ring-type colliders. The aim of this paper is twofold: to present a possibly complete list of papers on linac–ring-type collider proposals and to emphasize the role of linac–ring-type machines for future HEP research.

2.1. UNK+VLEPP (IHEP, Protvino)

In 1980's there were two energy frontier collider projects in the former USSR, namely, $\sqrt{s} = 6$ TeV proton-proton collider UNK and $\sqrt{s} = 2$ TeV linear electron-positron collider VLEPP. The construction of the first one was started at IHEP (Protvino, Moscow region), and the second one was planned at BINP (Novosibirsk). In mid 1980's the construction of VLEPP tangential to UNK was proposed in order to provide additional opportunity to handle energy frontier ep [8] and γp [9] colliders.

Luminosity estimations were given in [11]. Brief resume is followed. Two versions of placement of VLEPP regarding to UNK are possible, namely symmetric (Figure 3a) and asymmetric (Figure 3b). Two options of ep and γp collisions were considered for the UNK+VLEPP: on extracted proton beam (Figure 4a) or in proton ring (Figure 4b). It was shown that L = 10^{30} $cm^{-2}s^{-1}$ and L = 6×10^{30} $cm^{-2}s^{-1}$ could be achievable for first and second option, respectively.

Note that this consideration was the main scientific reason for moving of VLEPP from Novosibirsk to Protvino. Unfortunately, in final design VLEPP placement was chosen to cross the UNK ring, instead of tangential. Obviously, this choice closed ep and γp options (clear indication of collapse of Eastern Block).

Note that this consideration was the **main scientific reason for moving of VLEPP from Novosibirsk to Protvino.** Unfortunately, in **final design VLEPP placement was chosen to cross the UNK ring, instead of tangential**. Obviously, **this choice closed ep and γp options (clear indication of collapse of Eastern Block).**

Hopefully, CERN will not repeat similar mistake…