ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD3

PARTICLE COLLIDERS: OPTIONS FOR THE US AND INTERNATIONALLY

V. Shiltsev,* Northern Illinois University, DeKalb, IL, USA

Abstract

Frontier particle colliders, arguably among the largest, most complex, and advanced scientific instruments of modern times, have played a pivotal role in driving scientific discoveries in nuclear and high-energy physics for over six decades. Currently, conceptual studies and technical developments for several promising near- and medium-term future collider options are underway both in the US and internationally. In this presentation, we will briefly overview the most viable collider options in Asia, Europe, and the US, drawing upon insights from recent reports such as the European Particle Physics Strategy Update (2020), the Snowmass'21 (2021-23), the Particle Physics Project Prioritization Panel (P5) report (2023), and the Nuclear Science Advisory Committee (NSAC) report (2023). Additionally, we will touch upon the far-future prospect of ultimate ultrahigh-energy, low-luminosity colliders, potentially reaching or exceeding the 1 PeV center-of-mass energy scale.

INTRODUCTION

Understanding the universe critically depends on the fundamental knowledge of particles and fields, representing a central endeavor of modern nuclear and high-energy physics. Frontier particle colliders [1] — arguably among the largest, most complex, and advanced scientific instruments of modern times — have played a pivotal role in scientific discoveries in high-energy physics for many decades.

This May marks 60 years since the first operational high-energy particle colliders [2]. The idea of exploring collisions in the center-of-mass system to fully exploit the energy of accelerated particles (R. Wideroe, 1943) was practically realized in the early 1960s, almost concurrently, by three teams led by B. Touschek in Europe (AdA e^+e^- collider), by G. Budker in the USSR (VEP-1 e^-e^- collider), and by B. Richter in the US (CBX e^-e^- collider). Thanks to advances in technology and breakthroughs in beam physics, colliding beam facilities have progressed immensely and now operate at energies and luminosities many orders of magnitude greater than the pioneering instruments of the early 1960s.

In total, 31 colliders have reached the operational stage (some in several successive configurations); seven are currently operational (2024: VEPP-4M, BEPC, DAFNE, RHIC, LHC, VEPP-2000, Super-KEKB), and two are under construction (NICA, EIC).

While the Large Hadron Collider and the Super-KEKB factory represent the frontier hadron and lepton colliders of today, respectively, future colliders are an essential component of a strategic vision for particle physics. Conceptual studies and technical developments for several exciting near- and medium-term future collider options are underway in the US and internationally. In this presentation, we will briefly overview the most viable collider options in Asia, Europe, and the US, drawing upon insights from recent reports such as the European Particle Physics Strategy Update (EPPSU, 2020) [3], Snowmass'21(2021-23) [4, 5], the Particle Physics Project Prioritization Panel (P5) report (2023) [6], and the Nuclear Science Advisory Committee (NSAC) report (2023) [7].

Colliders for Nuclear Physics

At present, the international nuclear physics community is constructing two leading colliding beam facilities: EIC and NICA. The US 2023 NSAC Long Term Plan reads (Recommendation 2) [7]: "We recommend the expeditious completion of the EIC as the highest priority for facility construction." The Electron-Ion Collider (EIC), see Fig. 1, is currently under construction with expected start of physics operation ca. 2033. It is being built at Brookhaven National Laboratory (BNL), in a partnership with TJNAF. The EIC design [8] takes advantage of significant advances in accelerator and detector technologies, substantial investments in

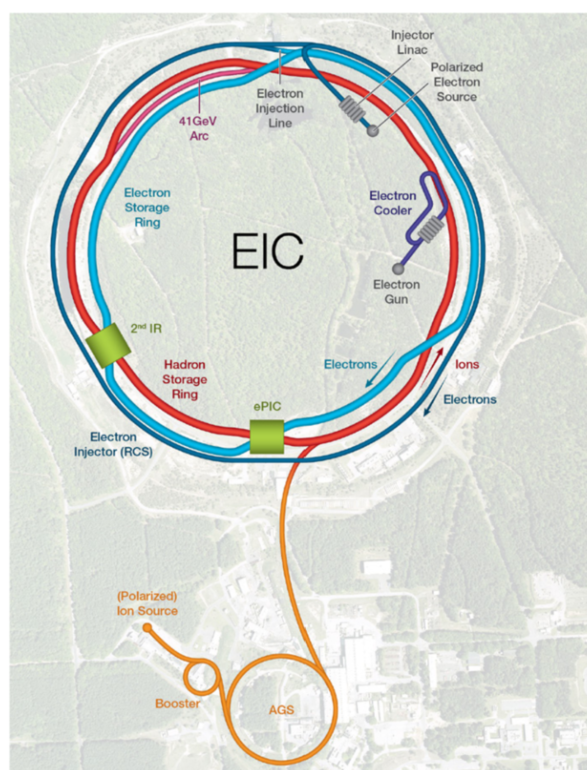

Figure 1: Schematic layout of the Electron-Ion Collider (EIC).

* vladimir.shiltsev@gmail.com

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD3

RHIC, and the unique expertise at BNL and Jefferson Lab, assumes collisions between 41–275 GeV proton beam circulating in the reconfigured RHIC 3.83-km long synchrotron and a 5-18 GeV electron beam stored in a new ring (ESR, in the same tunnel). The EIC physics requirements include highly polarized ($P_{e,n}$ ~70%) electron and nucleon beams (as the precision of measurements of interest scales as $LP_e^2P_n^2$), a spectrum of ion beams from deuterons to the heaviest nuclei (U or Pb), variable c.m.e. values from $\sqrt{s}$ =20 GeV to 140 GeV, high luminosities of up to 10^{33-34} cm^{-2}s^{-1}, as well as possibilities of having more than one interaction region. Main accelerator design challenges on the path to the required energy, luminosity, and polarization, include the development of SRF crab-cavities and advanced SC magnets for interaction region focusing, energy-recovery linac (ERL) based electron cooling of hadron beams, essential to attain luminosities two orders of magnitude beyond the predecessor HERA *ep* collider, and high intensity polarized particle sources, augmented by the development of special magnets and operational techniques to preserve the polarization through the acceleration process to the collisions, including swap-out injection.

NICA (Nuclotron-based Ion Collider fAcility) is a new accelerator complex under construction at the Joint Institute for Nuclear Research (JINR, Dubna, Russia) to study properties of hot and dense baryonic matter, strong interactions between quarks and gluons, and spin physics [9]. NICA will operate with a variety of beam species, ranging from protons and polarized deuterons to massive gold ions. The 500 m circumference SC magnet based collider will have 2 IPs and is designed for average luminosity in heavy ion and light ion interactions at the center of mass energies (c.m.e.) of 4-11 GeV with luminosity ~ 10^{27}cm^{-2}s^{-1} for a variety of nuclei up to $^{197}Au^{79+}$, and for polarized proton and deuteron collisions at 12–27 GeV c.m.e. with L=(1–10)×10^{31}cm^{-2}s^{-1}. The NICA project is now in its final stage of installation of its collider storage rings with the first collisions anticipated in late 2024 - early 2025.

HEP COLLIDERS

At present, the "collider frontier" belongs to the Large Hadron Collider with its 6.8 TeV energy per beam, 2.62·10^{34} cm^{-2}s^{-1} *pp* luminosity and some one TWh of annual total site electric energy consumption. The SuperKEKB is an asymmetric e^+e^- *B*-factory with 4 and 7 GeV beam energies, respectively. Since the startup in 2018, it has achieved the world record luminosity (for any collider type) of 4.71·10^{34} cm^{-2}s^{-1}, and aspires to reach 30·10^{34} cm^{-2}s^{-1}, a whopping 30-times over its predecessor KEK-B (1999-2010).

Several ambitious future collider proposals are under active discussions in Asia, Europe, and in the US.

HEP Colliders - Plans in Asia

The International Linear Collider (ILC, in Japan) e^+e^- will be a ~21 km-long 250(500) GeV c.m.e. facility that employs two linacs comprising about a thousand 1.3 GHz SRF cryomodules with average beam accelerating gradient of 31.5 MV/m. The cost estimate is about 7B$ (2017), incuding 10,000 FTEs of labor - see more details in [10] and below.

Chinese Electron Positron Collider (CEPC) is a 100 km circumference e^+e^- collider covering a range of EW/Higgs energies from 91 GeV to 360 GeV (later to be converted in a 75-125 TeV *pp* SPPC collider). Being very similar to the FCCee (see below), it has a TDR published in December of 2023 [11] and seeks a very aggressive schedule: Engineering Design Report phase in 2024-27, approval by the government in 2025, and construction in 2028-2035. There is very good progress demonstrated on all major components, including NC magnets, vacuum system, 650 MHz and 1.3 GHz SRF cavities, cryomodules and high efficiency klystron which will provide 60 MW to 100 MW of beam power to compensate for the synchrotron radiation (SR) losses. The project cost estimate is 36BCNY(~5.2B$), which does not accounts for labor, escalation, contingency, R&D, and spares.

HEP Colliders - Plans in Europe

The Future Circular Collider (FCC) at CERN (Fig. 2) [12] has been strongly supported by the 2020 EPPSU. Its first stage assumes construction of the FCCee a 91-km long e^+e^- Higgs Factory capable of operating over the range of energies from 91 GeV to 365 GeV (later to be converted in a 100 TeV *pp* FCChh collider) [13]. The FCCee main accelerator technologies are those of the NC magnets and 400MHz and 800 MHz SRF (to provide 100MW of the beam power to compensated the SR power losses). FCCee CDR (2018) estimates the facility cost ~ 12BCHF (not including labor, escalation, and contingency). Current vision of the FCCee project has following key milestones: March 2025 - FCC Feasibility Study Report to the European Strategy (with updated cost estimate); ca. 2028 - the project approval; ca. 2031 - start of the civil construction, ~2045 - start of the collider operation.

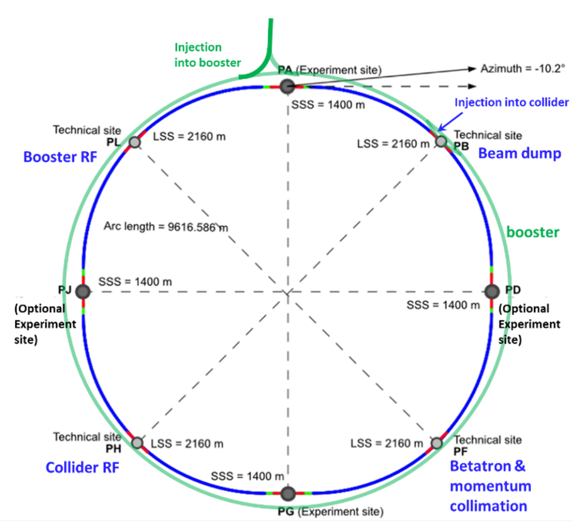

Figure 2: Layout of the FCCee collider at CERN.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD3

Another CERN-led proposal that has reached the CDR stage (2019) is linear e^+e^- collider CLIC [14]. Its physics scope is somewhat broader as not only it provides high luminosity at c.m.e. up to 380 GeV but also it can be extended to a 3 TeV facility. The 380 GeV machine is quite compact ~11 km because of an advanced 2-beam acceleration technology with 72-100 MV/m gradient in the 12 GHz warm copper RF structures. Its construction cost estimate is about 5.9 BCHF, not including some 11,500 FTEs of labor, escalation, or contingency.

HEP Colliders - Plans in the US

In 2021-2023, numerous future HEP collider proposals were discussed during the US high-energy physics community strategic planning exercise, Snowmass'21 [4]. The Snowmass'21 *Accelerator Frontier* [5] has established the Implementation Task Force (ITF) to evaluate proposed future accelerator projects for performance, technology readiness, schedule, cost, and environmental impact. Corresponding metrics have been developed for uniform comparison of proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron, and *ep* collider facilities; from those based on traditional and to advanced acceleration technologies. Reference [15] describes the metrics and approaches, and presents the comparative evaluations of future colliders performed by the ITF. Table 1 gives a high level summary of the ITF findings regarding the Higgs factory proposals and some 10+ pCM TeV future collider concepts: besides the c.m. energy, luminosity and facility power consumption (presented by the proponents), the table lists anticipated years of pre-project R&D (an indicator of the readiness for construction), years to the first physics (that includes the R&D time, pre-construction and construction - in the technically limited schedules which start at the time of the decision to proceed), and the cost range (understood as a total project cost - that includes explicit labor, etc. - without contingency and the inflation escalation, in 2021 BUSD). Note, that the ITF has uniformly used several models to estimate the cost (e.g., 5- and 31-parameters) as well as known costs of existing installations and reasonably expected cost of novel equipment. For future technologies, the cost estimates were quite conservative, and one should expect cost reductions from pre-project R&D.

The ITF report has provided a critically important assessment of future colliders. Firstly, it has shown that there is no clear winner in all the categories among the Higgs factory proposals. Indeed, in terms of the luminosity, the leading concepts are those based on the ERL technology (CERC, ReLiC, ERLC) while circular colliders FCCee and CEPC. The best prepared in terms of technical readiness (years of the pre-project R&D) are FCCee, CLIC, CEPC, and ILC (as noted above, the last two do have TDRs). ILC is the absolute leader in the category "Time to the 1st Physics" (estimated to be less than 12 years), followed by FCCee, CEPC, CLIC, and C3 (12-18). The electric power consumption is the lowest for CERC and XCC, the next cohort includes linear e^+e^- colliders ILC, CLIC, and C3. Last but not least, the lowest estimated costs are for the $\gamma\gamma$ collider XCC and $\mu\mu$ collider Higgs factory (note, that both will produce Higgs particles through s-channel that requires about half of the primary beams energy), while all the linear e^+e^- colliders ILC, CLIC, and C3 are placed in the next cost category.

As Table 1 indicates, all the very high energy collider proposals with 10 pCM (parton center of mass energy) TeV or above are generally more expensive then the Higgs factories, more power hungry, require significant investment in R&D and longer time to construct. Considered were *pp* colliders such as FCChh, SPPC and the Fermilab site-filler, advanced colliders based on the wakefield acceleration in plasma [16] and in very high frequency RF structures, and the muon colliders (at CERN [17] and at Fermilab [18]). The latter seem to be most appealing in all the categories of the ITF comparative analysis.

As the result, the 2023 P5 report [6] contains two recommendations specific to future colliders:

- *Recommendation 2c*: "An off-shore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies..."
- *Recommendation 4a*: "Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years..."

US Contribution to Off-shore Higgs Factories The US have been actively collaborating with the FCCee design team from the very beginning in the areas of theory, detectors, and accelerators. The US-FCC collaboration had been formed at the Annual Workshops in 2023 and 2024. The Snowmass'21 request to the P5 outlined several possible US contributions to the R&D and construction of the FCCee accelerators:

- *RF Systems:* 800 MHz SRF systems for Booster and Collider (that includes fabrication of 28 SRF cryomodules (CMs) for the FCC Higgs mode of operation and 244 SRF CMs for the FCC $t\bar{t}$ mode of operation); 800 MHz RF power sources (such as klystrons ≥80% efficiency); RF for 6-20 GeV e^+/e^- injector linac based on the C3 (cold copper RF) technology.
- *Magnets Systems:* IR magnets and cryostats (for 4 IRs); low magnetic field collider ring and Booster ring magnets; 14-20 T FCC-hh collider ring magnets.
- *Optics/Design/Instrumentation:* the Interaction Region (IR) design, and integrated machine design; beam polarization (simulations, design, fabrication of wigglers, etc); beam instrumentation (BPMs, feedback, etc).

While the ILC had its TDR since 2013 and is generally considered to be "shovel-ready", there is still no host country for the project (despite significant investments and efforts in Japan and from the ILC International Development

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD3

Table 1: The Snowmass'21 Implementation Task Force summary: main parameters of the Higgs factory proposals (FCCee, ILC, CLIC, C^3, HELEN, three ERL-based colliders, $\gamma\gamma$ and $\mu\mu$ Higgs factories), and several 10+ pCM TeV colliders (Muon Collider options, advanced wakefiled collider options, FCChh, and SPPC). Years of the pre-project R&D indicate required effort to get to sufficient technical readiness. Estimated years to first physics are for technically limited timeline starting at the time of the decision to proceed. The total project cost range is for the single listed energy in 2021$ (based on a parametric estimator and without escalation and contingency). All colliders listed above were assumed to be stand-alone projects, since ITF could not assume or decide on a sequence of projects. The peak luminosity and power consumption values have not been reviewed by ITF and represent proponent inputs. (Adapted from Ref. [15].)

Proposal	**CM Energy Nom. (Range) [TeV]**	**Lum./IP @ Nom. CME [10^{34} cm^{-2}s^{-1}]**	**Years of Pre-project R&D**	**Years to First Physics**	**Construction Cost Range [2021 B$]**	**Est. Operating Electric Power [MW]**
FCC-ee	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory	0.13	0.01	>10	19-24	4-7	200
Muon Collider at FNAL	10 (6-10)	20 (40)	>10	19-24	12-18	~300
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
pp Collider at FNAL	24	3.5 (7.0)	>10	>25	18-30	~400
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

team). Some R&D is still ongoing to demonstrate the required beam parameters (such as, e.g., the nano-beams in the ATF2 facility at KEK), to further improve performance and demonstrate industrialization of the 1.3 GHz SRF linac, and to develop alternative concepts (such as, e.g., electron linac-based positron source).

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD3

Muon Collider A colliding beam facility based on muons - has a number of advantages when compared to *pp* and e^+e^- machines. First, since the muon is a lepton, all of the beam energy is available in the collision - therefore giving a muon collider (MC) a factor of 7-10 advantage in the pCM energy wrt same beam energy *pp* colliders. That has a promise of a much more compact machine and a huge advantage $O(3)$ in the total facility cost. Second, since the muons are roughly 200 times heavier than electrons/positrons and thus emit around 10^9 times less synchrotron radiation than an electron beam of the same energy, it is possible to produce >10 TeV collisions in relatively compact circular collider - for example, a Fermilab site filler or with the circumference comparable to that of the LHC (or, potentially, even reusing the LHC tunnel; notably, the largest of the muon accelerator is the high energy booster RCS, not the collider itself, see Fig. 3). Finally, high-energy muon colliders are the most efficient machines in terms of power per luminosity. While the above arguments are highly appealing, there are several challenges with muons.

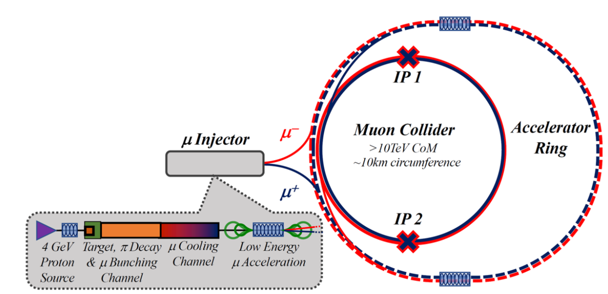

Figure 3: Schematic layout of a 10+ TeV muon collider [19].

Both the Snowmass'21 and the P5 report called for a comprehensive Muon Collider R&D program in the US, in close coordination with the CERN-based International Muon Collider Collaboration (IMCC). The areas of critical R&D towards the MC include design of the proton driver (in synergy with the FNAL PIP-II accelerator), targetry (in synergy with future Fermilab neutrino and precision muon programs), muon cooling design and optimization, accelerator lattice design, high-field magnet development (in synergy with the US Magnet Development Program), beam acceleration using superconducting RF technology, and mitigation of the neutrino induced radiation.In addition to accelerator R&D, strong efforts in refining the physics case and in conducting R&D for muon collider detectors, are necessary.

ULTIMATE COLLIDERS

The feasibility of future energy-frontier colliders typically hinges on the simultaneous attainment of at least five factors: c.m. energy E_{cm} feasibility, luminosity L, cost- and power-effectiveness, and reasonable construction time. The cost is critically dependent on acceleration technology used to reach the required E_{cm} while the cost limitations are not well defined, being dependent on such societal factors as the priority and availability of resources to support fundamental research.

For most collider types, the pursuit of high energy typically results in low(er) luminosity if the total facility annual power consumption (and, therefore, the average beam power) is limited. Depending on the collider type (see below) there are different sets of limiting factors which determining the ultimate luminosity, but in general, at very high energies approaching 1 PeV pCM and beyond the luminosity scales inversely with energy $L \propto 1/E_{cm}^{1...3}$, see Fig. 4. Correspondingly, it is hard to expect the luminosity above $O(1\ \mathrm{ab}^{-1}/\mathrm{yr})$ at the energies beyond 30 TeV (0.03 PeV).

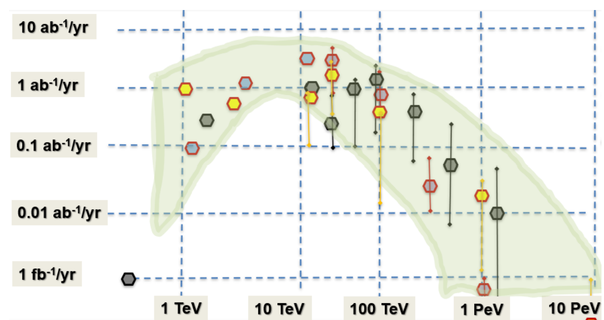

Figure 4: Annual integrated luminosity of some existing, designed and conceptually proposed colliders vs the "parton" center-of-mass energy. Black symbols are for circular *pp*-colliders (their pCM energy is taken to be $\sim E_{cm}/7$), yellow/red ones - for advanced linear e^+e^- and $\mu\mu$ colliders, and the blue/red ones - for circular muon colliders. (Adapted from Ref. [20]).

Reference [20] considers several anticipated main types of potential ultra-high energy colliders, and, assuming the facility cost limit of 3 times the LHC cost and the electric power consumption limit of 3 TWh/year, draws the following conclusions: i) the maximum c.m. energy reach for circular e^+e^- colliders is at ~0.5 TeV; ii) for linear RF-based lepton colliders and plasma $e^+e^-/e^-e^-/\gamma\gamma$ colliders, the limit is between 3 and 10 TeV; iii) for circular *pp* colliders the overall feasibility limit is close to or below ~10-14 TeV parton c.m.e. (35-50 TeV in each proton beam); iv) for circular $\mu\mu$ colliders the limit is about 30-50 TeV; v) there are exotic schemes, such as crystal channeling muon colliders, which potentially offer 100 TeV-1 PeV c.m.e., though at very low luminosity. All in all, muons seem to be the particles of choice for future ultimate HEP colliders.

ACKNOWLEDGEMENTS

I am indebted to S. Belomestnykh, D. Denisov, W. Fischer, S. Gourlay, B. List, S. Nagaitsev, M. Palmer, S. Posen, P. Raimondi, T. Raubenheimer, T. Roser, D. Schulte, S. Stapnes, D. Stratakis, G. Trubnikov, and A. Valishev for fruitful collaboration during the Snowmass'21 planning exercise, valuable insights on the topics related to future colliders, and comments on the draft of this presentation. I extend special thanks to Frank Zimmermann, my long-term collaborator and co-author on numerous publications and reviews pertaining to modern and future colliders.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD3

REFERENCES

[1] V. Shiltsev and F. Zimmermann, "Modern and future colliders", *Rev. Mod. Phys.*, vol. 93, p. 015006, 2021. doi:10.1103/RevModPhys.93.015006

[2] V. Shiltsev, "The first colliders: AdA, VEP-1 and Princeton–Stanford", Ch.2.1 in O. Bruning and S. Myers, Eds. *Challenges and Goals For Accelerators in the XXI Century*, New Jersey, USA: World Scientific, 2016, ISBN 978-981-4436-39-7.

[3] *2020 Update of the European Strategy for Particle Physics*, 2020, https://europeanstrategy.cern/european-strategy-for-particle-physics

[4] J. Butler *et al.*, "Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021) Summary Chapter", 2023. doi:10.48550/arXiv:2301.06581

[5] S. Gourla *et al.*, "Snowmass'21 Accelerator Frontier Report", 2022. doi:10.48550/arXiv:2209.14136

[6] H. Murayama *et al.*, "Report of the 2023 Particle Physics Project Prioritization Panel", 2023, https://www.usparticlephysics.org/2023-p5-report/

[7] G. Dodge *et al.*, "A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science", 2023, https://nuclearsciencefuture.org/

[8] F. Willeke *et al.*, "Electron Ion Collider Conceptual Design Report 2021", Brookhavel National Lab., Upton, NY, USA, Rep. BNL-221006-2021-FORE, 2021. doi:10.2172/1765663

[9] G. Trubnikov *et al.*, "NICA heavy-ion collider at JINR (Dubna). Status of accelerator complex and first physics at NICA", *J. Phys.: Conf. Ser.*, vol. 2586, p. 012013, 2023. doi:10.1088/1742-6596/2586/1/012013

[10] S. Michizono, "The International Linear Collider", *Nat. Rev. Phys.*, vol. 1, pp. 244–-245, 2019. doi:10.1038/s42254-019-0044-4

[11] The CEPC Study Group, "CEPC Technical Design Report – Accelerator (v2)", 2023. doi:10.48550/arXiv.2312.1436

[12] M. Benedikt, "Future Circular Colliders succeeding the LHC", *Nat. Phys.*, vol. 16, pp. 402–-407, 2020. doi:10.1038/s41567-020-0856-2

[13] S. Fleury, "FCC-ee large scale project installation planning: challenges & proposals", presented at the 14th Int. Particle Accel. Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper WECD1, this conference.

[14] S. Stapnes, "The Compact Linear Collider", *Nat. Rev. Phys.*, vol. 1, pp. 235–-237, 2019. doi:10.1038/s42254-019-0051-5

[15] T. Roser *et al.*, "On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force", *J. Instrum.*, vol. 18, p. 05018, 2023. doi:10.1088/1748-0221/18/05/P05018

[16] W. Leemans, "20 years since the first laser plasma accelerated dream beams and a look forward", presented at the 14th Int. Part. Accel. Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper FRXN2, this conference.

[17] C. Accettura *et al.*, "Towards a muon collider", *Eur. Phys. J. C*, vol. 83, p. 864, 2023. doi:10.1140/epjc/s10052-023-11889-x

[18] D. Stratakis, "The US effort towards making a Muon Collider", presented at the 14th Int. Particle Accel. Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper WECD3, this conference.

[19] K. Long *et al.*,, "Muon colliders to expand frontiers of particle physics", *Nat. Phys.*, vol. 17, p. 289, 2021. doi:10.1038/s41567-020-01130-x

[20] V. Shiltsev, "Ultimate Collider" (Oxford Encyclopedia, 2023). doi:10.1093/acrefore/9780190871994.013.118