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HIGH ENERGY FRONTIER DURING THE NEXT TWENTY YEARS

Abstract. Prospects and opportunities for particle physics accelerators at the energy frontier are reviewed. In particular, the main features characterizing hadron and lepton collider facilities proposed at CERN and in other known laboratories are discussed.

Keywords: hadrons, leptons, accelerators, colliders

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ПЕРСПЕКТИВЫ РАЗВИТИЯ ФИЗИКИ ВЫСОКИХ ЭНЕРГИЙ В БЛИЖАЙШИЕ 20 ЛЕТ И ДАЛЕЕ

Аннотация. Представлены перспективы развития и возможности физики ускорителей в области сверхвысоких энергий. Основное внимание уделено рассмотрению возможностей адронных и лептонных коллайдеров, планируемых в ЦЕРНе и других мировых центрах.

Ключевые слова: адроны, лептоны, ускорители, коллайдеры

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The availability of particle beams of ever increasing energy or intensity has accompanied the progress of particle physics over the last century. In the last forty years the search for the missing blocks of the standard model (i.e., bosons and fermions predicted by the standard theory) together with the need of measuring precisely their properties has been a major driver in defining the characteristic of accelerator projects such as LEP, Tevatron or LHC. The roadmap for future accelerators has made a major turn with the discovery of the Brout – Englert – Higgs scalar boson during the first years of run at LHC [1, 2]. Having found experimental evidence of all particles predicted by the standard theory, the exploration of the beyond-standard-model territory is now the main driver in designing machines for the energy frontier. We know that new physics exists because phenomena not incorporated in the standard theory have been observed: for example, the existence of dark matter or the presence of neutrino oscillations. There are also phenomena not naturally explained by the standard theory, as the matter-antimatter asymmetry of the universe, the hierarchical pattern of quark and lepton masses, or the lightness of the Higgs boson mass compared to the Plank scale. While search for new physics is nowadays a main driver we should not forget that for the first time we have the opportunity to measure the properties of a fundamental scalar boson. Are the couplings of the scalar boson to fermions and other bosons really as predicted by the standard theory? How electroweak physics behaves at high energy? (i.e., is the unitarity of WW scattering really preserved as foreseen by the Brout – Englert – Higgs mechanism?) Providing an answer to these questions is another major driver for defining new accelerator projects.

In these proceedings, some of the main accelerator projects at the energy frontier are reviewed, in particular hadron and lepton colliders. In the next Section the only already approved project, the High

Luminosity LHC upgrade, is discussed. Future circular e^+e^- and proton-proton colliders are discussed next, followed by e^+e^- linear colliders. Recent ideas for designing muon colliders are reported at the end.

1. The High Luminosity LHC upgrade (HL-LHC). The Large Hadron Collider at CERN is currently our main tool for the exploration of the energy frontier, and offers the means to explore the forefront of Standard Model physics and beyond. The collider has recently reached a centre-of-mass energy of 13 TeV and has already surpassed by a factor of almost two its design instantaneous luminosity (10^{34} cm^{-2}s^{-1}), running with 2556 bunches and a bunch spacing of 25 ns. At current peak luminosity about 40 generic hadronic interactions are superimposed in each event (*pileup*). The planned Long Shutdown 2 (LS2, see Fig. 1) involves several upgrades to the detectors and to the injector complex, which will enable an increase in beam current and reach a total of 300 fb^{-1} of proton-proton collisions by 2022. At that point, the LHC machine as well as the ATLAS and CMS detectors are expected to undergo an extensive upgrade phase in order to cope with an integrated luminosity 10 times higher than design and bring the total integrated luminosity to 3000 fb^{-1} (and possibly 4500 fb^{-1}) by the mid 2030's. This phase is called High Luminosity LHC upgrade (HL-LHC).

At HL-LHC the maximum instantaneous luminosity is kept below 5 10^{34} cm^{-2}s^{-1} in order to increase beam lifetime and integrated luminosity (*luminosity leveling*) [3], corresponding to around 140 pileup events per bunch crossing. Various options for beam structures are under investigations, for example a scheme based on 25 ns spacing with 8 bunches and 4 empty bunches can alleviate the e-cloud problem while keeping the pile up at 140, at a price of relatively small loss of luminosity.

The main features of the upgrade are briefly mentioned here. Wide aperture niobium-tin (Nb_3Sn) quadrupoles will be used to replace the present inner triplet quadrupole magnets. Given the aperture (150 mm) and the peak field (>12 T) these quadrupoles have a stored energy per unit length twice as larger as the one of the LHC dipoles. Wider aperture and revision of the insertion optics and layout will allow a squeeze, expressed in term of the β^* parameter, of 15 cm. In order to reach such a low β^* value, a new optics scheme called ATS (Achromatics Telescopic Scheme) will be employed to overcome the limitation of the matching section and of the sextupole correction circuits. Dipoles with field of 11 T, again made of Nb_3Sn, will be used to make room for collimators in the cold dispersion suppressors. Enhanced collimators will be installed for the beams, reaching a stored energy of 500 MJ. Wide aperture niobium-titanium (NbTi) separator magnets (the first twin aperture magnets moving away from the interaction point) will be employed. Finally Crab cavities, which are high-frequency RF transverse deflectors providing quasi head-on-collisions at the interaction point, will be used to compensate the luminosity reduction factor caused by the large crossing angle.

A novel scheme, named *crab-kissing* [4] is also under investigation to alleviate the pile up density issue. By turning the bunches also in the perpendicular plane (beside rotating them in the crossing plane to reduce the angle), the longitudinal pile up density can be reduced by a factor two. This enhanced set of parameters may enable to run with a leveled instantaneous luminosity of 7.5 10^{34} cm^{-2}s^{-1} and a total pile up of 200.

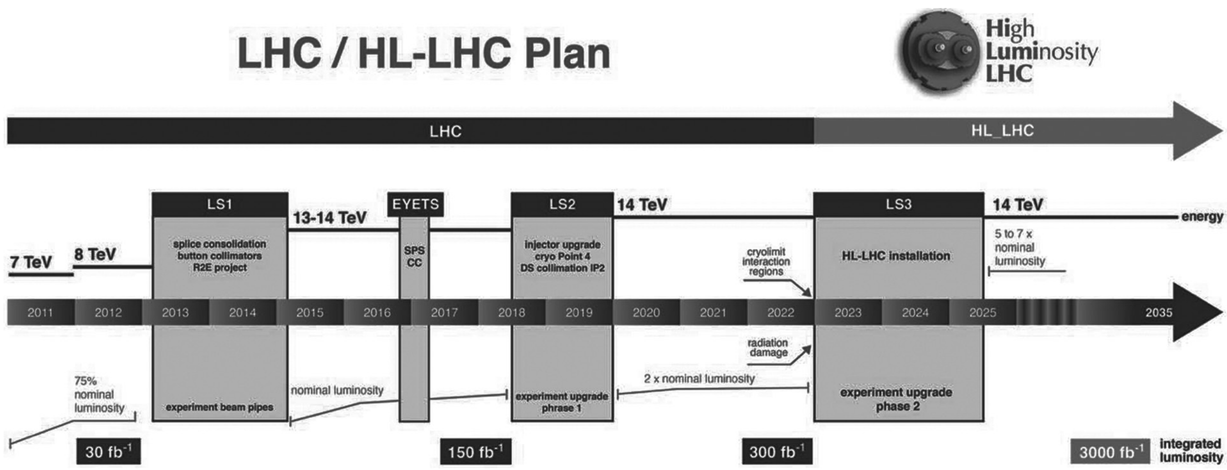

Fig. 1. Current LHC programme, showing the HL-LHC phase

2. The Future Circular Collider: electrons and positrons (FCC-ee). The Future Circular Collider (FCC) concept builds on the successful experience with the LEP-LHC tunnel. A possible long-term strategy for high-energy physics at colliders, after the exploitation of the LHC following its High Luminosity upgrade, is based on a tunnel of about 100 km circumference, which takes advantage of the present CERN accelerator complex. In a first phase the tunnel could host an e^+e^- collider (FCC-ee) at centre-of-mass energy between the Z pole and above the top-quark-pair production threshold, with a subsequent proton proton collider as an ultimate goal. Together with a possible electron-proton option, the project would provide 50 years of physics at the highest energies. Fig. 2 shows a possible location for FCC in the Geneva area.

The potential of a very large e^+e^- circular collider has drawn considerable attention following the Higgs boson discovery. The Higgs boson mass is low and not far from the hedge of LEP sensitivity, about 115 GeV, which is only 10 % lower than the mass actually measured at LHC, i.e. 125 GeV. The highest centre-of-mass energy attainable at a circular collider is limited by radiation losses by the beam. Synchrotron energy loss per turn goes as E^4/ρ, where E is the beam energy and ρ the radius of the ring. An increase of the radius by a factor three, which is roughly the ratio between the proposed FCC and the LEP radii, would be sufficient to produce the 125 GeV Higgs boson with about one half of the RF power utilised at LEP. A collider with such a large ring would also give an excellent opportunity to perform precision measurements at the Z pole, at the WW production threshold and at the ttbar production threshold, providing a unique discovery potential by combining precision measurements and direct searches.

The FCC-ee design is based on an accelerator ring with a storage ring delivering continuous top-up injection. The storage ring compensates for the small beam lifetime caused by Bhabha scattering and loss of particles in collisions, providing a constant level of luminosity [5]. The multi bunch operation foresees more than 16000 bunches with beams of 45.6 GeV (Z pole) and about 100 bunches with beams of 175 GeV (ttbar production threshold). Fig. 3 shows the FCC-ee expected instantaneous luminosity as a function of the centre-of-mass energy, if the luminosity is delivered at two interaction points. The highest luminosity is reached at the Z pole, as expected from the previous considerations. The behaviour is clearly complementary to linear colliders (discussed later in these proceedings): much higher luminosity can be reached at a centre-of-mass energy up to ttbar threshold, while linear colliders can potentially reach a much higher centre-of-mass energy. A project with design similar to FCC-ee, called CEPC, is presently under discussion in China [6].

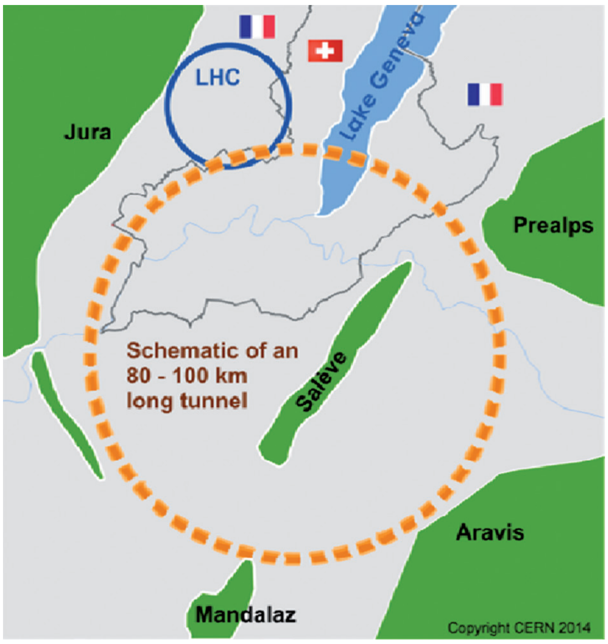

Fig. 2. A possible location for the 100 km FCC tunnel in the Geneva area close to CERN

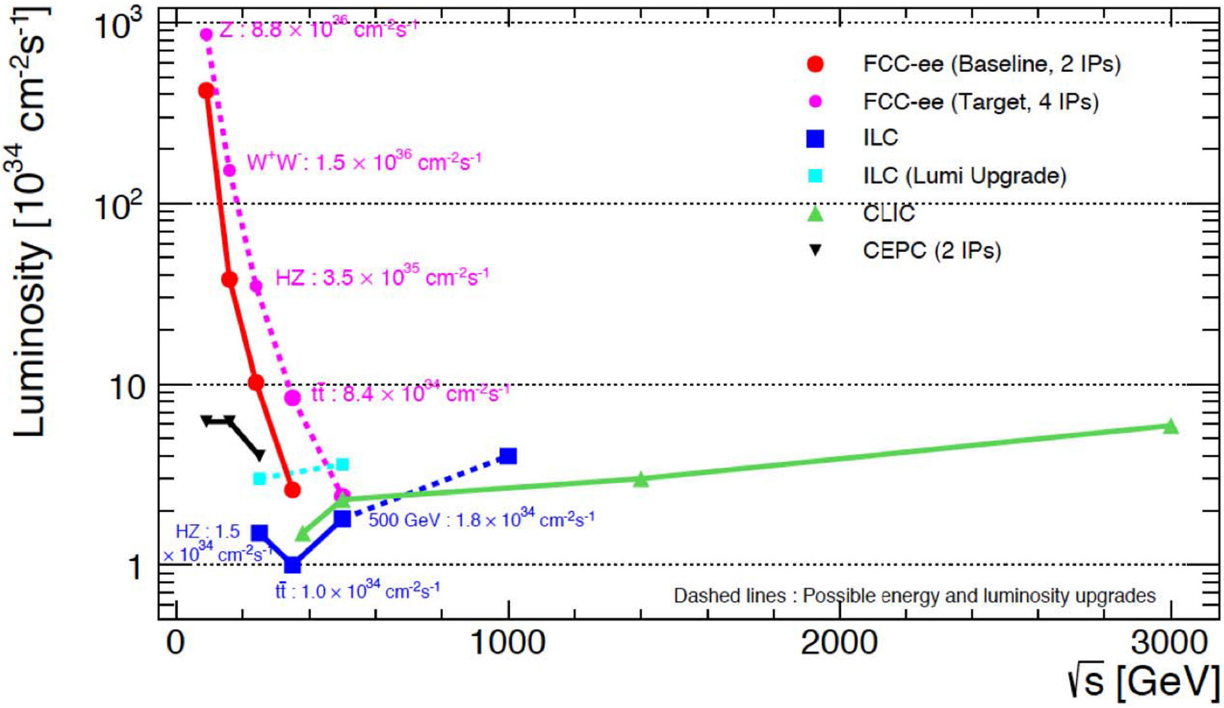

Fig. 3. Instantaneous luminosity, in units of 10^{34} $cm^{-2}s^{-1}$, expected at FCC-ee (full red line), in a configuration with two interaction points operating simultaneously, as a function of the centre-of-mass energy. For illustration, the luminosities expected at linear colliders, ILC (blue line) and CLIC (green line), are indicated in the same graph. The plot includes further luminosity and energy upgrades for ILC and FCC-ee (dashed lines), under discussion at the time of writing. The performance of one of the possible design options for CEPC is also indicated (black line)

3. The Future Circular Collider: proton proton collisions at 100 TeV (FCC-hh). The physics potential for a high-luminosity proton proton collider at centre-of-mass energy of 100 TeV is decribed in Ref. [7]. One of the main technological challenges for such a collider is the development and construction of the large number of magnets required. A dipole field of 16 T, which is envisaged as the ultimate goal for low temperature superconducting alloys, corresponds to a machine with a circumference of 100 km in order to reach 100 TeV. A shorter machine (80 km) would be possible if high temperature superconducting (HTS) 20 T magnets become available.

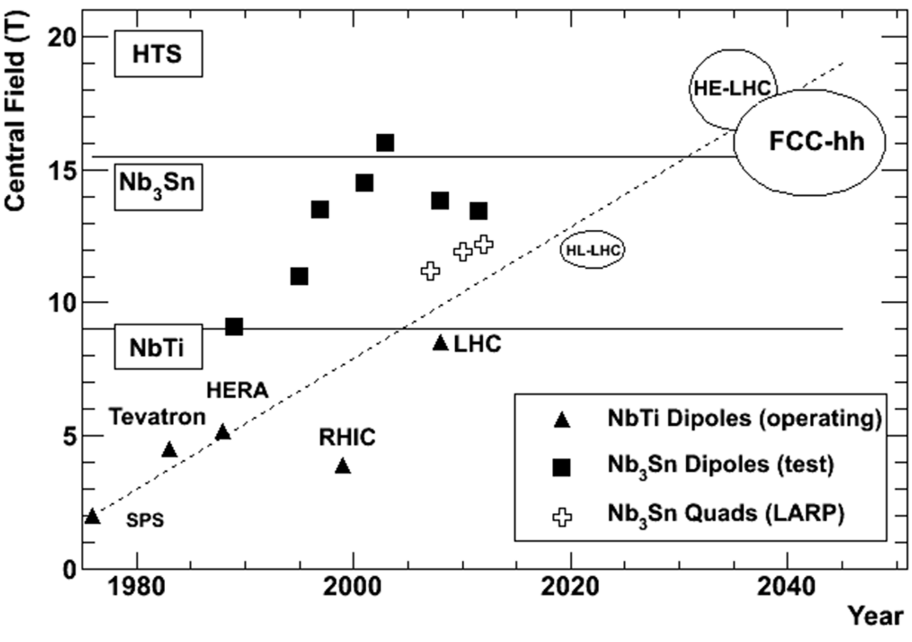

Fig. 4. Evolution of the maximum dipole field for hadron colliders

A key factor for sustaining the increase in magnetic field is superconductor performance. As clearly shown in Fig. 4, LHC dipoles are near the limit of possibility for Nb-Ti technology. The HL-LHC project explores the use of Nb_3Sn, which is a much more complex and difficult superconductor. However, it enables reaching 12 Tesla and beyond, up to 15–16 T. To go toward higher fields, HTS based technology is needed. Nb_3Sn has been developed in these last 10 years for HL-LHC, which provides also an ideal demonstrator on a reasonable scale of such technology, so far never used in accelerators. However, to push the Nb_3Sn technology toward its limit of 15–16 T, a further important step in Nb_3Sn performance is needed, improving its critical current by 50 %. Obtaining this performance step is among the main objectives of the FCC-hh design and R&D phase, to be concluded around 2020 with a 16 T dipole magnet demonstrator.

4. Linear colliders with electron and positron beams (ILC and CLIC). The idea of a high-energy linear collider based on superconducting RF cavities dates back to the pioneering work done by the TESLA collaboration in the nineties. The current project, the International Linear Collider (ILC) [8], foresees a high-luminosity linear electron-positron collider based on 1.3 GHz superconducting radio-frequency (SCRF) accelerating technology. The possibility of obtaining high-gradient with SCRF has been demonstrated at the TESLA test facility at DESY where 35 MV/m have been reached. The same technology foreseen for the ILC is being employed at the European X-ray free-electron laser (XFEL), a 17.5 GeV linear accelerator operating at DESY.

The centre-of-mass-energy range foreseen for the ILC is from 200 to 500 GeV, extendable to 1 TeV. At the ILC beams are produced by a polarised electron source based on a photocathode DC gun and a polarised positron source in which positrons are obtained from electron-positron pairs by converting high-energy photons. These photons are produced by passing the high-energy main electron beam through an undulator. Electron and positron damping rings (DR) with a circumference of 3.2 km are housed in a common tunnel and host beams of 5 GeV. Beams are transported from the damping rings to the main linacs, where are injected after bunch-compression. The two main linacs utilise the already mentioned 1.3 GHz SCRF cavities operating at an average gradient of 31.5 MV/m, with a pulse length of 1.6 ms. Two beam-delivery systems, each 2.2 km long, bring the beams into collision with a 14 mrad crossing angle, at a single interaction point which can be occupied by two detectors in a so-called push-pull configuration.

The total length of the ILC complex, expected to be hosted in Japan, is 31 km. The electron source, positron source and the electron and positron damping rings are expected to be centrally located around the interaction region. The damping-ring complex is displaced laterally to avoid interference with the detector hall. The electron and positron sources themselves are housed in the same (main accelerator) tunnels as the beam-delivery systems, in order to reduce the overall cost and size of the central-region underground construction.

The CLIC scheme [9] represents to date the only available technology to build an electron-positron collider in the multi-TeV energy range keeping reasonable accelerator length, cost and power consumption. In this scheme, the required RF power is provided by a low-energy high-intensity drive beam, which is decelerated in dedicated *power-extraction and transfer structures* (PETS) feeding accelerating structures for the main high-energy beam. A dedicated CLIC test facility at CERN (CTF3) is devoted to prototyping and technological studies. At CTF3 a high-current drive beam generates the 12 GHz RF power for accelerating structures, with a drive beam of 4 A and up to 120 MeV. An accelerating gradient of 145 MeV/m has been achieved, demonstrating the CLIC concept. In the current design [10] the two main accelerators of CLIC accelerate electrons and positrons from 9 GeV to 1.5 TeV in one pass, reaching a centre-of-mass energy of 3 TeV.

5. Muon Colliders. Muon beams represent an attractive choice for high energy lepton colliders because of the negligible level of synchrotron radiation, compared to electron beams. The physics potential of muon colliders is well known since a long time [11]. Muon colliders have recently received renewed attention with the discovery of the Higgs boson thanks to their possible role as a Higgs factory of relatively small size. In addition, with muon colliders it would be possible to go well beyond the multi-TeV centre-of-mass energy with lepton beams.

The use of muon beams in a collider is challenging for several reasons, not the least of which is that muons are unstable particles. In the original proposal, muons are produced in sufficient amount by the decay of pions produced via fixed-target collisions of an intense proton beam. Pions must then be captured by superconducting solenoids in a drift region for their subsequent decay to muons. The resulting muon beam has a very large spread in energy and very large emittance, therefore muon cooling is a crucial component of muon colliders.

An alternative technique has been recently proposed to overcome the necessity of muon cooling, by naturally producing low-emittance high energy muon beams [12]. In this new proposal muon pairs are produced at threshold with the process $e^+e^- \rightarrow \mu^+\mu^-$ by hitting a light-Z target with a positron beam of 45 GeV, which corresponds to the minimum momentum required to produce a muon pair in the centre-of-mass system. With an intense 45 GeV positron source, one could produce high-rate and low-emittance μ^+ and μ^- beams of 22.5 GeV each, to be subsequently accelerated and used for experiments in a dedicated accelerator complex.

Conclusions. The design and construction of energy frontier accelerators is a twenty years long enterprise, as shown by the construction of LHC. Decisions for next future accelerators have to be taken by the end of this decade, in order to continue the exploration of particle physics at the energy frontier after the end of operations at HL-LHC. Relevant decisions are expected to be taken at next meeting on *European Strategy for Future Accelerators*, which will take place in 2019.

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References

1. ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B*, 2012, vol. 716, no. 1, pp. 1–29. Doi: 10.1016/j.physletb.2012.08.020

2. CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Physics Letters B*, 2012, vol. 716, no. 1, pp. 30–61. Doi: 10.1016/j.physletb.2012.08.021

3. Koutchouk J. P. Luminosity optimization and leveling. *Proceedings of Chamonix 2010 workshop on LHC Performance*. Switzerland, 2010, pp. 342–347.

4. Fartoukh S. Pile up management at the high-luminosity LHC and introduction to the crab-kissing concept, *Physical Review Special Topics – Accelerators and Beams*, 2014, vol. 17, no. 11, p. 111001. Doi: 10.1103/physrevstab.17.111001

5. Blondel A., Zimmermann F. *A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson*. 2012. Available at: https://arxiv.org/ftp/arxiv/papers/1112/1112.2518.pdf.

6. *CEPC-SPPC Preliminary Conceptual Design Report, IHEP-CEPC-DR-2015-01.* Available at: https://inspirehep.net/record/1395734/

7. Mangano M. L. (Ed.). Physics at the FCC-hh, a 100 TeV pp collider. *CERN Yellow Report*, 2017, vol. 3. Available at: https://e-publishing.cern.ch/index.php/CYRM/issue/view/35/showToc

8. Asner D. M (et al.). *ILC Higgs White Paper*. 2013. Available at: https://arxiv.org/pdf/1310.0763.pdf.

9. Schnell W. A two stage RF linear collider using a superconducting drive LINAC. Puglisi M., Stipcich S., Torelli G. (eds). *New Techniques for Future Accelerators*. Boston, Springer, 1987, pp. 67–87. Doi: 10.1007/978-1-4684-9114-2_5

10. Aicheler M., Burrows P., Draper M., Garvey T., Lebrun P., Peach K., Phinney N., Schmickler H., Schulte D., Toge N. *A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report*. 2014. Doi: 10.2172 / 1120127

11. Cline D. Physics potential of a few 100-GeV μ^+ μ^- collider. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated* Equipment, 1994, vol. 350, no. 1-2, pp. 24–26. Doi: 10.1016/0168-9002(94)91150-9

12. Antonelli M., Boscolo M., Di Nardo R., Raimondi P. Novel proposal for a low emittace muon beam using positron beam on target. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2016, vol. 807, pp. 101–107. Doi: /10.1016/j.nima.2015.10.097

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