Current Landscape of High Energy Physics Colliders

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1.1.1 Colliders of the past and present

Particle accelerators have been widely used for physics research since the early 20th century and have greatly progressed both scientifically and technologically since then. To gain an insight into the physics of elementary particles, one accelerates them to very high kinetic energy, let them impact on other particles, and detect products of the reactions that transform the particles into other particles. It is estimated that in the post-1938 era, accelerator science has influenced almost 1/3 of physicists and physics studies and on average contributed to physics Nobel Prize-winning research every 2.9 years [1]. Colliding beam facilities which produce high-energy collisions (interactions) between particles of approximately oppositely directed beams did pave the way for progress since the 1960's. Discussion below mainly follows recent publication [2].

Twenty nine colliders reached operational stage between the late 50's and now. The energy of colliders has been increasing over the years as demonstrated in Fig.1. There, the triangles represent maximum CM energy and the start of operation for lepton (usually, $e+e-$) colliders and full circles are for hadron (protons, antiprotons, ions, proton-electron) colliders. One can see that until the early 1990's, the CM energy on average increased by a factor of 10 every decade and, notably, the hadron colliders were 10-20 times more powerful. Since then, following the demands of high energy physics, the paths of the colliders diverged to reach record high energies in the particle reaction. The Large Hadron Colider (LHC) was built at CERN, while new $e+e-$ colliders called "particle factories" were focused on detail exploration of phenomena at much lower energies.

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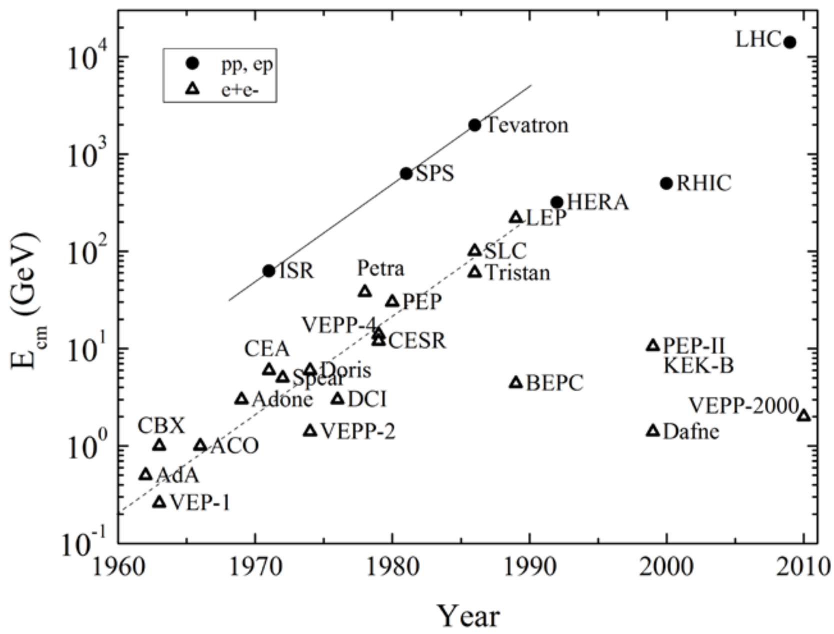

Figure 1: Colliders over the decades (from [2]).

Figure 2 demonstrates impressive progress of luminosities of colliding beam facilities since the invention of the method. Again, the triangles are lepton colliders and full circles are for hadron colliders. One can see that over the last 50 years, the performance of the colliders has improved by more than 6 orders of magnitude and reached record high values of over $10^{34}cm^{-2}s^{-1}$. At such luminosity, one can expect to produce, e.g., 100 events over one year of operation (about 10^7 s) if the reaction cross section is 1 picobarn (pb)=10^{-39} cm^2.

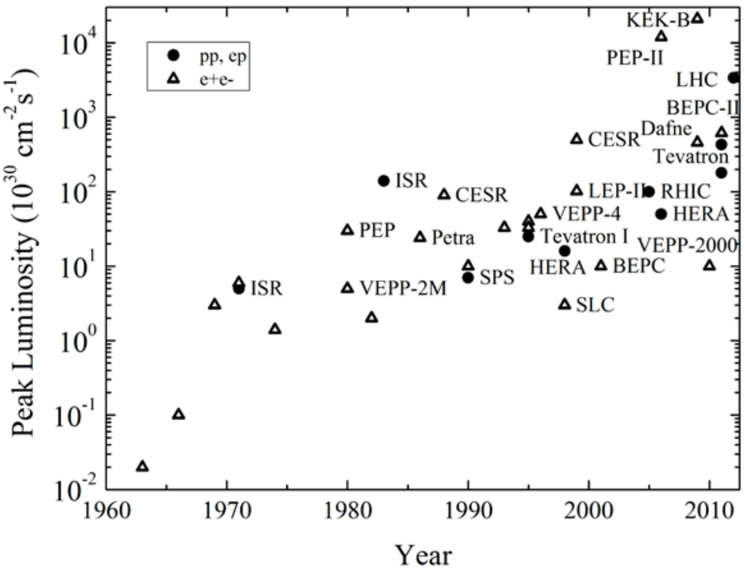

Figure 2: Peak luminosities of particle colliders.

Table 1: Past, present and possible future colliders; hadron colliders are in **bold**, lepton colliders in *Italic*, facilities under construction or in decisive design and planning stage are listed in parenthesis (…).

	early 1990‘s	early 2010’s	2030’s
Europe	**H*E*RA,** (**LHC**)	**LHC** (*Super-B*, **HL-LHC,**	**HE-LHC**
	LEP (Dafne)	**LH*e*C,** *E***NC**)	*CLIC?*
Russia	*VEPP-2, VEPP-4*	*VEPP-2000*, *VEPP-4M*	**NICA** ?
	(**UNK**, *VLEPP*)	(**NICA**, *Tau-Charm*)	*Higgs Factory* ?
United States	**Tevatron**, (**SSC**)	**RHIC**	*Muon Collider* ?
	SLC, *CESR*, (*PEP-II*)	(*e***RHIC**, *EL***IC**)	*PWLA/DLA* ?
Asia	*Tristan, BEPC*	*BEPC*	*ILC* ?
	(*KEK-B*)	(*Super-KEKB*)	*Higgs Factory* ?
Total	9 (7)	5 (9)	1 + ?

In general, one may say that colliders have had 50 glorious past years as not only many important particle discoveries were made at them, but they also initiated a wide range of innovation in accelerator physics and technology which resulted in 100-fold increase in energy (for each hadron and lepton colliding facilities) and 10^4-10^6 fold increase of the luminosity. At the same time, it is obvious that the progress in the maximum c.m. energy has drastically slowed down since the early 1990's and the lepton colliders even went backwards in energy to study rare processes – see Fig.1. Moreover, the number of the facilities in operation has dropped from 9 to 5, as indicated in Table 1 which lists all operational colliders as of the early 1990's and now (early 2010's) and accounts for the projects under construction or under serious consideration at this time (in parenthesis). Our current landscape shows the end of the Tevatron era (the 26 years long ~2 TeV c.m. energy proton-antiproton Collider Run ended in September 2011) and is dominated by the LHC at CERN. The Tevatron, LEP and HERA established the Standard Model (SM) of particle physics. The next generation of colliders is expected to explore it at deeper levels and to eventually lead the exploration of the smallest dimensions beyond the current SM.

1.1.2 Colliders of the near future (next 10 to 20 years)

The future of the collider is ultimately driven by the demands of particle physics, but should stay within the limits of the available technologies and financial resources. All the projects currently under construction or at the design stage (see Table 1) satisfy those three requirements and, thus, have good prospects of becoming operational and deliver results in the next 20 years. Schematically they can be categorized by the area of the promising physics as follows:

Energy Frontier : the LHC luminosity upgrade project HL-LHC [3] will employ novel SC magnet technology based on the Nb_3Sn superconductors for tighter focusing at the interaction points and quintuple the performance of the energy frontier machine by mid-2020's to $5\cdot10^{34}$cm^{-2}s^{-1} with luminosity levelling at 14 TeV c.m. energy in proton-proton collisions and will enable to obtain about 250 fb^{-1} of the integrated luminosity per year with ultimate goal of 3000 fb^{-1} for both ATLAS and CMS experiments.

Low-energy hadron collisions: investigation of the mixed phase of quark–gluon matter and polarization phenomena at relatively low hadron energies has recently become of significant interest for the high energy physics community, and it is the main goal of the Nuclotron-based Ion Collider fAcility (NICA) currently under construction at JINR

(Dubna, Russia) [4]. NICA will allow for the study of ion-ion (Au^{+79}) and ion-proton collisions in the energy range of 1-4.5 GeV/amu with average luminosity of 10^{27} cm^{-2} s^{-1} and also polarized proton-proton (5-12.6 GeV) and deuteron-deuteron (2-5.8 GeV/amu) collisions – in that regime luminosities up to 10^{31} cm^{-2} s^{-1} are foreseen. The plans indicate start of operation and first physics results later in this decade.

Electron-hadron collisions: deep inelastic electron-nucleon scattering is in the focus of a new electron-hadron collider project, the LHeC [5], in which polarized electrons of 60 GeV to possibly 140 GeV collide with LHC protons of 7000 GeV with design luminosity of about 10^{33} $cm^{-2}s^{-1}$. This would exceed the integrated luminosity collected at the previous *ep* collider HERA at DESY by two orders of magnitude in a 20 times wider kinematic range in the momentum transfer Q^2. Similar approach of reusing an existing beam facility and adding an accelerator for another species is taken in two collider projects in the US – eRHIC at BNL [6] and Electron-Ion Collider (ELIC) at JLab [7]. The eRHIC design is based on one of the existing RHIC(Relativistic Heavy Ion Collider) hadron rings which can accelerate polarized nuclear beam to 100 GeV/nucleon and polarized protons upto 250 GeV for, and a new 20-30 GeV multi-pass energy-recovery linac (ERL) to accelerate polarized electrons; the luminosity varies from 10^{33} $cm^{-2}s^{-1}$ to 10^{34} $cm^{-2}s^{-1}$ depending on the energy and species. The ELIC proposal re-uses the CEBAF 3-7 GeV polarized electron accelerator and requires the construction of a 30 to 150 GeV storage ring for ions (*p, d, ^3He* and *Li*, and unpolarized light to medium ion species). The attainment of very high luminosities in the ELIC, from $5\cdot10^{33}$ $cm^{-2}s^{-1}$ to 10^{35} $cm^{-2}s^{-1}$, an ERL-based continuous electron cooling facility is anticipated to provide low emittance and simultaneously very short ion bunches. Though with lower c.m. energy than LHeC, both of the projects in the US have the advantage of colliding both electron and ion species with polarized spins. It is believed that not more than one of the two can be supported and constructed.

Complementary physics programs can be realized at the proposed electron-nucleon collider ENC at the upcoming Facility for Antiproton and Ion Research FAIR at GSI Darmstadt (Germany) by utilizing the 15 GeV antiproton high-energy storage ring HESR for polarized proton and deuteron beams, with the addition of a 3.3 GeV storage ring for polarized electrons [8]. This will enable electron-nucleon collisions up to a center-of-mass energy upto 14 GeV with peak luminosities in the range of 10^{32} to $10^{33} cm^{-2}s^{-1}$.

<u>*Electron-positron factories:*</u> In the late 1990's – early 2000's, two asymmetric-energy $e+e-$ *B*-factories, the KEKB collider for the Belle experiment at KEK and the PEPII collider for the BaBar experiment at SLAC, had achieved tremendous success in confirmation of the Standard Model (SM) in the quark flavor sector and indicated that the Kobayashi-Maskawa mechanism is the dominant source of the observed *CP* violation in nature. Despite that, two fundamental questions remain unanswered in the flavor sector of quarks and leptons: a) it is not clear why the SM includes too many parameters and b) there is still a serious problem with the matter-antimatter asymmetry in the universe. To extend physics reach beyond two *B*-factories, much higher (by a factor of 40 or so) luminosity Super-*B* factories are either set up or considered for construction – one in Italy [9] and another in Japan [10]. Both are asymmetric-energy $e+e-$ colliders with beam energies of about 4 GeV and 7 GeV and with a design luminosity approaching 10^{36} cm^{-2} s^{-1}, which is to be achieved via somewhat higher beam currents and very small beta-functions at the interaction points $\beta_y^* \sim 0.3$mm made possible by employment of the above mentioned "crab waist" scheme. The physics run of the Super-KEKB in Japan is expected in 2015 and the physics run will start in 2015. Ultimately, Belle II detector should collect 40 times more *B*-meson samples per second than its predecessor – roughly 800 *BB* pairs per second and accumulate an integrated luminosity of 50 ab^{-1}=50,000 fb^{-1} by 2021.

Many similar technical solutions, e.g. the "crab waist", will also be employed in the project of TauCharm factory in Novosibirsk (Russia) [11] which calls for c.m. collision energy variable from 3 GeV to 4.5 GeV (from *J/psi* resonances to charm barions), luminosity in excess of 10^{35} cm^{-2} s^{-1} and longitudinal polarization of at least one (electron) beam.

If one will project at the very end of the next 20 years, then the landscape of the collider physics is much less certain, there are several directions to advance and the choice between the options will be based upon the results from the LHC. The relevant results are expected to be available starting in 2012-13 (e.g., anticipated discovery of the Higgs boson) but they might easily slip well into the 2020's. Let us look into five possibilities for an after-LHC collider of 2030's.

Higher energy LHC: One of the most feasible opportunities is an energy upgrade of the LHC to 33 TeV c.m. proton-proton collisions [12]. The HE-LHC in the existing LHC tunnel will require 20T dipole magnets which are currently thought possible via combination of the NbTi, Nb_3Sn and HTS (high-temperature superconductor) SC magnet technology. Such a collider could follow the HL-LHC and start operation in the early 2030's. Despite the (presumed) feasibility of the machine, its energy reach is limited to ~2.5 times the LHC energy and it is not fully clear yet whether such a (relatively) small energy advance will justify its construction.

Higgs Factory: If the Higgs boson is discovered at the LHC in the presently anticipated range of its masses m_H=115-135 GeV range, the detailed studies and precise measurements of this unique spin-0 elementary particle might be of enough significant interest to justify construction of a *e+e-* collider – a dedicated "Higgs factory". The maximum cross-section, and arguably the optimal centre-of-mass energy for studies of a number of Higgs boson properties, is at $E_{cm} \sim m_{\mathrm{H}} + (110\pm10)$ GeV ~250 GeV, and several opportunities for the facility are now under discussion, including one based on the ILC-type linear collider (see below) as well as several ring-ring versions [13]. The biggest challenge for the latter is the requirement to replenish energy loss of electrons and positrons due to the synchrotron radiation of the order of 10 GeV per turn even in 20-km or longer tunnels - see Eq.(8) – that with necessity means extensive use of high gradient SC RF accelerating cavities. Other challenges toward attainment of the required luminosity of ~10^{34} cm^{-2} s^{-1} (equivalent to 20,000 events per year under assumption of the $e+e- \rightarrow HZ$ cross section of about 200 femtobarn (fb)=$2\cdot10^{-34}$ cm^2) will be significant electric power consumption on the order of 100 MW needed for continuous acceleration of ~10 mA of beam current and the need for very small beam emittances and very large momentum acceptance of the ring to accommodate the energy losses at the interaction points (see discussion on the *beamstrahlung* effect below). A cost saving option of the Higgs factory in an existing tunnel, e.g., 26.7 km long LHC tunnel or 21 km long UNK tunnel, looks particularly attractive.

Alternative way for production of the Higgs bosons is in the reaction $\mu+\mu- \rightarrow H$ (so called *s-channel* reaction) which has advantageously large cross section for muons,

$(m_\mu/m_e)^2$~40,000 times higher than for electrons, and (another advantage) needs a $\mu+\mu$- collider with factor of two lower c.m. energy E_{cm}~m_H. The third advantage of that scheme is significantly smaller c.m. energy spread $\delta E_{cm}/E_{cm}$~ 0.01-0.003% (compared to ~0.2% for the $e+e$- factories) that allows much better study of the outstandingly narrow width Higgs particle decays [14]. Production of ~4,000 events per year will require luminosity of at least 10^{31} cm^{-2} s^{-1} which seems to be very challenging because of the short muon lifetime and difficulties of the muon production (see discussion on high energy muon colliders below).

Energy Frontier Lepton Collider: It is presently widely believed that a multi-TeV lepton collider will be needed to follow the LHC discoveries. The most viable options currently under consideration are $e+e-$ linear colliders ILC (International Linear Collider) [15] and CLIC (Compact Linear Collider) [16] or $\mu+\mu-$ Muon Collider [17]. Each of these options has its own advantages, challenges and issues [18, 16].

Table 2: Comparison of Lepton Collider alternatives

	ILC	CLIC	MC
c.m energy, TeV	0.5	3	1.5-4
c.m. energy spread, rms	~2%	>5%	~0.1%
Luminosity , cm^{-2}s^{-1}	$2\cdot10^{34}$	$2\cdot10^{34}$ *	$(1\text{-}4)\cdot10^{34}$
Feasibility report	2007	2012	2014-16
Technical design	2013	2016	~2020
Number of elements	38,000	260,000	10,000
Hi-Tech length, km	36	~60	14-20
Wall plug power, MW	230	580	~140

* peak luminosity within 1% c.m. energy spread

The biggest challenge for the linear $e+e$- colliders is to accelerate the particles to the design energy within a reasonable facility footprint and with as high as possible power conversion from the "wall-plug" to the beams. The ILC employs pulsed 1.3GHz SC RF cavities with average accelerating gradient of 33.5 MV/m, has the total length of the 0.5 TeV c.m. energy facility of about 31 km and has design power efficiency (beam power/total AC power) of about 8%. CLIC scheme is based on two-beam acceleration in 12 GHz normal conducting RF structures with average gradient of 100 MV/m, the total length of the main tunnel of 3 TeV c.m. collider is 48 km and overall beam power efficiency is ~5%. Both projects have in principle demonstrated technical feasibility of their key acceleration technologies. Both have very tight requirements on the beam emittance generated in several km long injection rings, emittance preservation in the main linacs where beam is subject of minuscule transverse kicks due to vibrations and other dynamic misalignments, and need for ultimate precision beam position monitors to stabilize beam trajectories on every shot using fast beam-based feedback systems. The stability tolerances are even tighter for the elements of several-km long "final focus" systems – accelerator beamlines to focus beams to unprecedented beam sizes of σ^*_y/σ^*_x=6nm/640nm in the ILC and 0.9nm/45nm in CLIC. Another "not-so-easy" to get around challenge is the c.m. energy spread induced by beamstrahlung (the energy loss caused by radiation of gamma quanta by the incoming electron due to its interaction with the EM field electron (positron) bunch moving in the opposite direction) during the very moment of collision of short bunches with rms length of σ_z =50-300 μm, that for parameters of interest can be approximated as :

$$\frac{\delta E}{E} \propto \frac{\gamma N^2 r_e^3}{\sigma_x^2 \sigma_z} \quad , \tag{1}$$

and reach several % or even 10% - see Table 2. The induced radiation generates undesirable background in the detectors, makes handling of the beams after the collision more sophisticated and, most importantly, sets limitation on the energy resolution of the narrow resonances such as in the expected Higgs- and *Z'*-boson decay reactions.

Muons, which can be thought of as a heavy electrons, are essentially free of all synchrotron radiation related effects, which are proportional to the fourth power of the Lorentz factor γ^4, and, thus, $(m_\mu/m_e)^4 = (207)^4 = 2\times10^9$ times smaller. So, a multi-TeV $\mu^+\mu^-$ collider [18] can be circular and therefore have a compact geometry that will fit on existing accelerator sites, e.g., Fermilab's. The collider has a potentially higher energy reach than linear *e+e-* colliders, its c.m. energy spread in a 1.5-4 TeV $\mu^+\mu^-$ collider can be as small as 0.1%, requires less AC power and operates with significantly smaller number of elements requiring high reliability and individual control for effective operation - see Table 2. Additional attraction of a Muon Collider(MC) is its possible synergy with the Neutrino Factory concept [19] as beam generation and injection complex of that facility and of a MC are similar (perhaps identical) [20]. As mentioned above, due to higher mass of the muon and superb energy resolution, a Higgs factory based on low(er) energy $\mu^+ \mu^-$ collisions is very attractive, too.

The biggest challenges of a MC come from the very short lifetime of the muon - τ_0=2μs is just long enough to allow acceleration to high energy before the muon decays into an electron, a muon-type neutrino and an electron-type antineutrino ($\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$) – and from the methods of the muon production as tertiary particles in the reactions $pN \rightarrow \pi + ... \rightarrow \mu + ...$, so, the beams of muons are generated with very large emittances. A high-energy, 1-5 TeV c.m., high- luminosity $O(10^{34})$ cm^{-2}s^{-1} muon collider seems will require a factor of $O(10^6)$ reduction of the 6-dimensional muon beam phase space volume (muon cooling). Though there has been significant progress over the past decade in developing the concepts and technologies needed to produce, capture and accelerate muon beams with high intensities on the order of $O(10^{21})$ muons/year, the feasibility of the high luminosity multi-TeV muon collider can be claimed only after demonstration of the fast ionization cooling of muons and resolution of the related issue of normalconducting RF cavities breakdown in strong magnetic fields. The latter is expected to be addressed by 2014-16, while convincing demonstration of the 6D cooling might take another 4 to 6 years [18].

Possible options for ultra-high energy colliders for the time scale beyond 20 years from now are outlined in Ref.[2].

1.1.3 References

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