LUMINOSITY TARGETS FOR FCC-hh*

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Abstract

We discuss the choice of target values for the peak and integrated luminosity of a future high-energy frontier circular hadron collider (FCC-hh). We review the arguments on the physics reach of a hadron collider. Next we show that accelerator constraints will limit the beam current and the turnaround time. Taking these limits into account, we derive an expression for the ultimate integrated luminosity per year, depending on a possible pile-up limit imposed by the physics experiments. We finally benchmark our result against the planned two phases of FCC-hh [1, 2, 3]

INTRODUCTION

The proposed peak luminosity targets for future hadron colliders vary from values lower than 10^{33} cm^{-2}s^{-1} [4] to others in excess of 10^{36} cm^{-2}s^{-1} [5].

However, much more important than the peak luminosity of a collider is the useful luminosity accumulated over time, i.e. its integrated luminosity delivered to one or several particle-physics detectors over several years.

In this paper we discuss the necessary and achievable values of integrated luminosity for future higher energy hadron colliders, such as the FCC-hh, looking at both physics arguments and technical constraints.

PHYSICS REQUIREMENTS

For e^+e^- colliders the relevant cross sections decrease with the inverse energy squared, $\propto 1/E^2_{\rm c.m.}$, which requires the luminosity to increase with the square of the energy. In the case of hadron colliders the situation is more complex, since hadrons are not fundamental particles, but consist of partons (quarks and gluons). At hadron colliders, to produce a new particle at a given energy, it is generally much more efficient to increase the hadron beam energy than to raise the hadron-collider luminosity, since the constituent (parton) luminosities at the energy of interest rapidly increase with higher beam energy. To elucidate the impact of integrated luminosity on the energy reach of the FCC-hh [1, 2], Fig. 1 compares the reach of a 100-TeV pp collider, FCC-hh, at three different integrated luminosities (3, 25 and 100 ab^{-1}) with the one of the HL-LHC (3 ab^{-1} at 14 TeV). The lines represent the rough average for various types of parton interactions (e.g. valence quark, sea quark, and gluon scattering).

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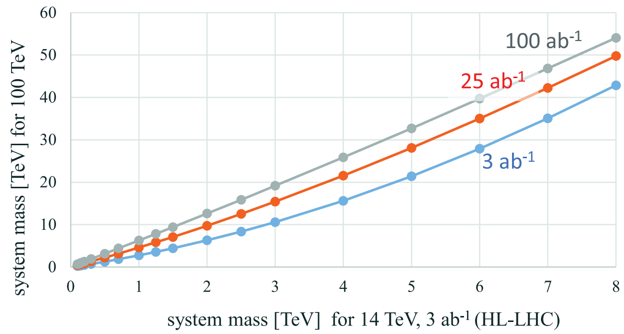

Figure 1: Relative energy reach of a 100-TeV pp collider, FCC-hh, with an integrated luminosity of 3 ab^{-1}, 25 ab^{-1}, or 100 ab^{-1} compared with the one of the 14-TeV HL-LHC at 3 ab^{-1}. Shown is the parton-parton system mass for an equal number of events, assuming that acceptance and efficiency remain the same. Parton luminosities and associated energy reach were computed using the tool of Ref. [6].

For example, the total number of events at 2 TeV with the HL-LHC would be equal to the one found at an energy of about 6 TeV with the FCC-hh at 3 ab^{-1}, about 10 TeV at 25 ab^{-1}, and 12 TeV at 100 ab^{-1}, i.e. an additional increase 300% in integrated luminosity raises the energy reach by merely 20%.

A much more comprehensive study considering a number of specific physics scenarios [7] confirms that a total integrated value of 20–25 ab^{-1} for each of two experiments is a reasonable luminosity goal for a future 100-TeV hadron collider.

CROSS SECTIONS

The energy-dependent total and inelastic cross sections, $\sigma_{\rm tot}$ and $\sigma_{\rm inel}$, can be estimated from the scaling laws [8, 9, 10, 11],

$$\sigma_{\rm tot}\ [\rm mbarn] \approx 42.1 s^{-0.467} - 32.19 s^{-0.540} + 35.83 + 0.315 \ln^2\left(\frac{s}{34.0}\right) , \quad (1)$$

and [12, 13]

$$\sigma_{\rm inel}\ [\rm mbarn] \approx \sigma_{\rm tot} - 11.7 + 1.59 \ln s - 0.134 \ln^2 s , \quad (2)$$

where s designates the square of the centre-of-mass energy in units of GeV^2. At 14 TeV c.m. the total and inelastic cross sections are then expected to be 112 mbarn and 83 mbarn, respectively [9]. At 100 TeV they will increase to 156 mbarn and 110 mbarn.

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BEAM INTENSITY

The total beam intensity is limited by the synchrotron radiation in the arcs, and the associated demand for refrigerator power, to a beam current of 0.5 A or about

$$N_{\rm b,0} = 10^{15} \tag{3}$$

protons per beam [3, 14]. This value corresponds to a total synchrotron radiation power of 5 MW emitted inside the cold arcs, which will be intercepted with a beam screen held at a temperature of either 40–50 K or 80–100 K (depending on the mass of the cold bore).

TURNAROUND TIME

The turnaround time $t_{\rm ta}$, is the average time interval between the end of one physics fill and the restart of the detector data taking on the next fill.

A portion of this turnaround time is needed for injection into the two collider rings. Other portions of the turnaround correspond to the ramp-up and ramp-down times of the collider, the time required for a possible magnet pre-cycle, for β^* squeeze, and for collimator set up, etc.

The injection period must accommodate the cycles of a (smaller) "high-energy booster" as well as any additional time intervals spent in the pre-injector complex. The ideal minimum filling time is estimated at 0.5–1.0 h [15].

Considering the LHC, with increased ramp speed [16], as the high-energy booster (i.e. the injector for the collider), the average turnaround time, $t_{\rm ta}$, of the FCC-hh collider is expected to be 5 hours in Phase I, and only 4 hours in a later Phase II [3].

PROTON BURN-OFF

The proton burn off in collision is described the equation

$$\frac{dN_{\rm b}(t)}{dt} = -n_{\rm IP} L \sigma_{\rm tot} \ , \tag{4}$$

where $\sigma_{\rm tot}$ denotes the total cross section, $n_{\rm IP}$ the number of collision points, L the instantenous luminosity, and $N_{\rm b}(t)$ the total number of protons per beam at time t.

EVENT PILE UP

An important constraint on the peak luminosity is the maximum event pole up.

This event pile up in the particle physics detectors, μ, is approximately equal to the number of inelastic scattering events per bunch collision. It can, therefore, be calculated from the formula

$$\mu \equiv \sigma_{\rm inel} \frac{L}{n_{\rm b} f_{\rm rev}} = \sigma_{\rm inel} \frac{N_{\rm b}^2}{4\pi\beta^*\epsilon} \ , \tag{5}$$

where $\sigma_{\rm inel}$ refers to the (inelastic) cross section for any event "seen" by the particle-physics experiment.

The existing LHC high-luminosity detectors were designed for a nominal event pile up of about 20–25 events per bunch crossing. During LHC run 1 they have demonstrated that twice this value can be dealt with (at twice the nominal bunch spacing, i.e. 50 ns instead of 25 ns).

For the HL-LHC runs, the ATLAS and CMS detectors will be upgraded to emable them to accept a constant pile up around 140 (with luminosity leveling) or pile-up peaks of up tp 200 in case the luminosity decays during a fill.

We may expect a further advance in detector technology for the FCC-hh, either permitting shorter bunch spacings with the same limit on the pile up or a higher maximum pile up. Over the next two decades an increase by a factor 5 to about 1000 events per crossing appears conceivable.

The maximum acceptable pile up $\mu_{\rm max}$ implies a minimum fill duration of

$$t_{\rm fill,min} = \frac{N_{\rm b,0}\sigma_{\rm inel}T_{\rm rev}}{n_{\rm IP}\sigma_{\rm tot}n_{\rm b}\mu_{\rm max}} \ , \tag{6}$$

which for $\mu_{\rm max} = 1000$ or 500 amounts to 3 or 6 hours, respectively.

AVERAGE LUMINOSITY

Integrating Eq. (4) the luminosity accumulated during a single fill is

$$\int_{t=0}^{t=t_{\rm fill}} L \; dt = \frac{\Delta N_{\rm b}}{n_{\rm IP}\sigma_{\rm tot}} \le \frac{N_{\rm b,0}}{n_{\rm IP}\sigma_{\rm tot}} \ , \tag{7}$$

where $N_{\rm b,0}$ signifies the total number of protons per beam at the start of the collisions, and $\Delta N_{\rm b} = \int_{t=0}^{t_{\rm fill}} (dN_{\rm b}/dt) dt$ the number of protons consumed during a physics fills.

The time-averaged luminosity can then be expressed as

$$< L >= \frac{\int_{t_{\rm fill}} L dt}{t_{\rm fill} + t_{\rm ta}} \le \frac{N_{\rm b,0}}{n_{\rm IP}\sigma_{\rm tot}(t_{\rm fill} + t_{\rm ta})} \ . \tag{8}$$

Equation (8) sets an upper limit on the average luminosity per fill, which is valid independently of the specific luminosity evolution during a fill (e.g. emittance shrinkage due to radiation damping, emittance control by noise exctitation, beam-beam tune shift limits, pile-up limits, etc. [3]).

The highest average luminosity could be obtained with a nearly instant burn-off, $t_{\rm fill} \to 0$. However, the complete burnoff in a single collision, or a few, would entail an extremely high event multiplicity, as well as unbearable beam-beam tune shifts, and likelihood of beam-loss induced aborts. For optimum overall efficiency it appears reasonable to consider a fill length comparable to the turnaround time $t_{\rm fill} \approx t_{\rm ta}$. In this case

$$< L > \approx \frac{N_{\rm b,0}}{2 n_{\rm IP}\sigma_{\rm tot}t_{\rm ta}} \ . \tag{9}$$

With an optimistic average turnaround time $t_{\rm ta} = 4$ h, $n_{\rm IP} = 2$, the time-average luminosity of the FCC can now be estimated at $< L > \approx 10^{35}$ cm^{-2}s^{-1}.

INTEGRATED LUMINOSITY

The integrated annual luminosity can simplistically be estimated by multiplying the total time scheduled for physics production T, the machine availability A (defined as the time without hardware failures divided by the total time scheduled), and the average luminosity over the time periods without any hardware failure, as

$$L_{\rm int} \equiv \int_{\rm year} L(t)dt = T_{\rm tot} A < L > \; . \tag{10}$$

Considering an availability A of 71%, i.e. the value achieved at the LHC in the year 2012 [17], and assuming that $T_{\rm tot} = 160$ days are scheduled for physics per year, we can use (10) to estimate the integrated luminosity for the FCC-hh as 1 ab^{-1} per year.

Inserting (6) into (8), we can express the integrated luminosity of (10) as

$$L_{\rm int} \leq T_{\rm tot} A \frac{N_{\rm b,0}}{n_{\rm IP}\sigma_{\rm tot} t_{\rm ta} + \frac{N_{\rm b,0}\sigma_{\rm inel} T_{\rm rev}}{n_{\rm b}\mu_{\rm max}}} \; . \tag{11}$$

From this equation we can also deduce that for operation in a pile-up-limit dominated regime the turnaround time should be smaller than

$$t_{\rm ta,pu} \leq t_{\rm fill,min} = \frac{N_{\rm b,0}\sigma_{\rm inel} T_{\rm rev}}{n_{\rm IP}\sigma_{\rm tot} n_{\rm b}\mu_{\rm max}} \; . \tag{12}$$

Figure 2 shows the integrated luminosity per year as a function of the maximum acceptable pile up, for three different values of turnaround time. A turnaround time of 5 h and a maximum pile up $\mu_{\rm max} = 180$ are assumed for FCC-hh Phase I. For Phase 2 these are pushed to $t_{\rm ta} = 4$ h and $\mu_{\rm max} = 940$, respectively [3]. As one can see the target parameters, based on a detailed calculation of all beam parameters during a physics store, are close to the maximum possible annual luminosity, for design beam current and turnaround times.

CONCLUSIONS

In this article we have derived, or discussed, some general upper bounds on the average and integrated luminosity of a future 100-TeV hadron collider, FCC-hh.

Annual luminosities of 0.2–2 ab^{-1} are possible, depending on the turnaround time and on the maximum acceptable event pile up.

Accumulating about 20–25 ab^{-1} over 20–25 years of operation is also a good match to the physics discovery potential of this machine.

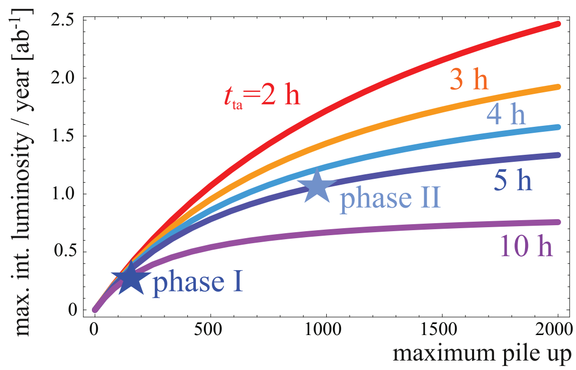

Figure 2: Maximum integrated luminosity per year as a function of maximum pile-up, assuming 160 days of physics run, a machine availabilty A of 71%, two primary collision points ($n_{\rm IP} = 2$), $n_{\rm b} = 10600$ bunches per beam, and a maximum beam intensity of $N_{\rm b,0} = 10^{15}$ protons. The various curves correspond to different average turnaround times $t_{\rm ta}$. The design working points for FCC-hh Phases I and II [3] are also indicated.

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