RHIC Collider Projections (FY2004 – FY2008)

Thomas Roser, Wolfram Fischer

Last update: August 20, 2003

This note discusses in Part I possible operating modes for the RHIC Run-4 (FY2004) running period including constraints from cryogenic cool-down, machine set-up and beam commissioning. In Part II a 5-year projection is given for gold-gold and polarized proton collisions.

Part I – Run-4 Projections

Cryogenic operation – After the summer shutdown the two RHIC rings will be at room temperature. They will be first brought to liquid nitrogen temperature, in about 10 days. Then, two weeks will be required to cool down to 4 Kelvin. At the end of the run, one week of refrigerator operation is required for the warm-up to 80 Kelvin.

Running modes – A number of running modes are considered in RHIC, such as Au-Au collisions, polarized proton collision, and Si-Si collisions. For each mode we should plan for 2 weeks of machine set-up with the goal of establishing collisions, and a 3-week machine development period ("ramp-up") after which stable operation can be provided with integrated luminosities that are a fraction of the maximum goals shown below. During the ramp-up period detector set-up can occur, however with priority for machine development.

Higher weekly luminosities can be achieved with a continuous development effort in the following weeks. At this year's RHIC retreat is was proposed to use the day shifts from Monday to Friday for this effort, with enough personnel available in the following shift to ensure production during the evening and night shift. The luminosity development efforts should stop when insurmountable limits, posed by the current machine configuration, are reached. After a running mode has been established, a change in the collision energy can be achieved in about 2 weeks (1 week set-up and 1 week ramp-up).

For example, the expected 27 weeks of RHIC refrigerator operation during FY2004 could be scheduled in the following way for two RHIC operating modes:

Cool-down from 80K to 4K	2 weeks
Set-up mode 1	2 weeks
Ramp-up mode 1	3 weeks
Data taking mode 1 with further ramp-up	7 weeks
Set-up mode 2	2 weeks
Ramp-up mode 2	3 weeks
Data taking mode 2 with further ramp-up	7 weeks
Warm-up	1 week

Since the highest weekly luminosities are reached at the end of each mode, the integrated luminosities are maximized with long runs in each mode, and as few mode changes as possible.

Past performance – Table 1 shows the Au-Au luminosities achieved at the end of the Run-2 (FY2001/02), and the p-p luminosities achieved in Run-3 (FY2003). The quoted average store luminosity was for a store with no hardware problems and with a luminosity that agreed well with predicted values from intensity and beam emittance (store # 1812 for Au-Au, # 3810 for p-p). The ratio of average weekly luminosity over store luminosity was 27% and 33% for Au-Au and p-p, respectively. Note that this includes all interruptions such as maintenance and studies.

Table 1: Achieved beam parameters and luminosities for Au-Au (Run-2) and p-p (Run-3).

Mode	# bunches	Ions/bunch $[10^9]$	β* [m]	Emittance [μm]	$\mathcal{L}_{peak}$ $[cm^{-2}s^{-1}]$	$\mathcal{L}_{store\ ave}$ $[cm^{-2}s^{-1}]$	L_{week}
Au-Au	55	0.6	1	15-40	3.7×10^{26}	1.5×10^{26}	24 $(\mu b)^{-1}$
(p↑-p↑)	55	70	1	20	6.0×10^{30}	3.0×10^{30}	0.6 $(pb)^{-1}$

Luminosity projections – Table 2 lists the expected maximum peak and average luminosities for the possible modes in FY2004 that could likely be achieved after a sufficiently long running period, typically many weeks, unless thus far unknown machine limitations are encountered. With experience from past runs we expect luminosities at the end of the 3-week ramp-up period to be lower than at the end of the running period by about an order of magnitude. For all modes it was assumed that the beam energy is 100 GeV/nucleon. The average store luminosity is for a good store as defined above. This is a number predictable from the beam parameters. The weekly integrated luminosity was then obtained by using a ratio of 40% between average weekly and average store luminosity, based on our experience from d-Au running. The expected diamond rms length is 20 cm due to the availability of the full voltage from the 200 MHz storage cavities.

Note that the quoted luminosities are for β* = 1 m. This is *only* available at PHENIX and STAR. PHOBOS and BRAHMS are limited to β* ≥ 3 m due to the lack of nonlinear IR correctors. β* at PHOBOS is further limited by the beam abort system in IR10, and may need to be larger than 3 m. For p-p running these luminosities can only be provided at two IRs simultaneously due to limitation from beam-beam effects. Due to the required abort gaps in both beams, collisions of 56 bunches can only be provided for two opposing IPs. The other IPs will have a 10% reduction in the number of collisions.

Table 2: Maximum luminosities that can be reached after a sufficiently long running period.

Mode	# bunches	Ions/bunch $[10^9]$	β* [m]	Emittance [μm]	$\mathcal{L}_{peak}$ $[cm^{-2}s^{-1}]$	$\mathcal{L}_{store\ ave}$ $[cm^{-2}s^{-1}]$	L_{week}
Au-Au	56	0.9	1	15-40	12×10^{26}	3×10^{26}	70 $(\mu b)^{-1}$
(p↑-p↑)	56	100	1	20	11×10^{30}	6×10^{30}	1.4 $(pb)^{-1}$
Si-Si	56	7	1	20	5×10^{28}	2×10^{28}	5 $(nb)^{-1}$

Time dependence of integrated luminosity – Since we expect many weeks of continuous ramp-up to reach the maximum weekly luminosities, the total integrated luminosities will be strongly time dependent. This is illustrated in Figure 1 and Figure 2, which show as a function of time the integrated Au-Au and p-p luminosities achieved in Run-2 and Run-3, respectively, as well as projections for Run-4. For the projected minimum it is assumed that the demonstrated weekly luminosity, given in Table 1, is reached after 16 weeks of linear ramp-up, starting after 3 weeks of set-up. Whether luminosity gains will occur in a linear fashion or be discontinuous is beyond our present ability to predict. For the projected maximum it is assumed that the weekly luminosity in Table 2 is reached instead of the demonstrated weekly luminosity. For p-p the assumptions are the same with the exception that the initial luminosity after the "ramp-up" period for both minimum and maximum expectations was 0.4 $(pb)^{-1}$ as demonstrated in Run-3.

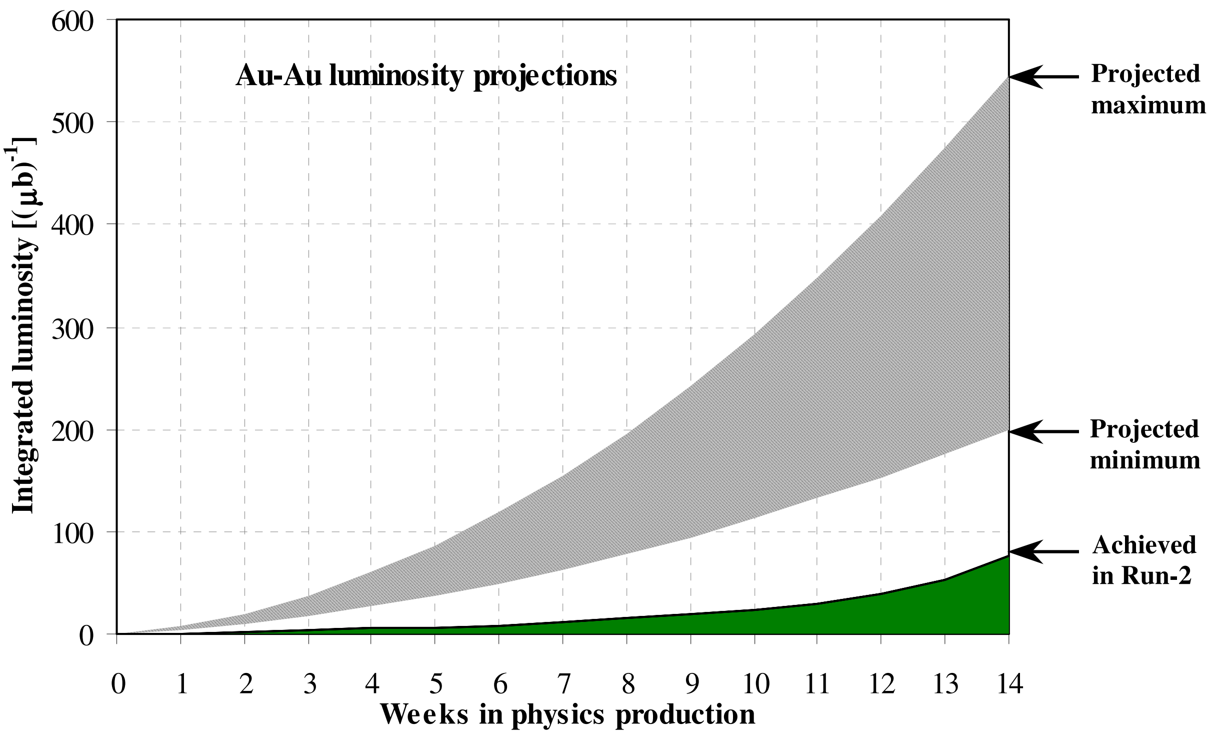

Figure 1: Integrated Au-Au luminosity achieved in Run-2, and projected minimum and maximum integrated luminosities for Au-Au collisions, assuming linear weekly luminosity ramp-up in 16 weeks.

Impact of mode switching – Table 3 shows the impact of mode switching on the integrated luminosity. Compared are the total integrated luminosities per mode for a run with 1 mode (19 weeks of data taking) and 2 modes (7 weeks/mode of data taking). In both cases it is assumed that the weekly luminosity can be increased linearly in time, and that the minimum or maximum weekly luminosities are reached after 14 weeks of data taking.

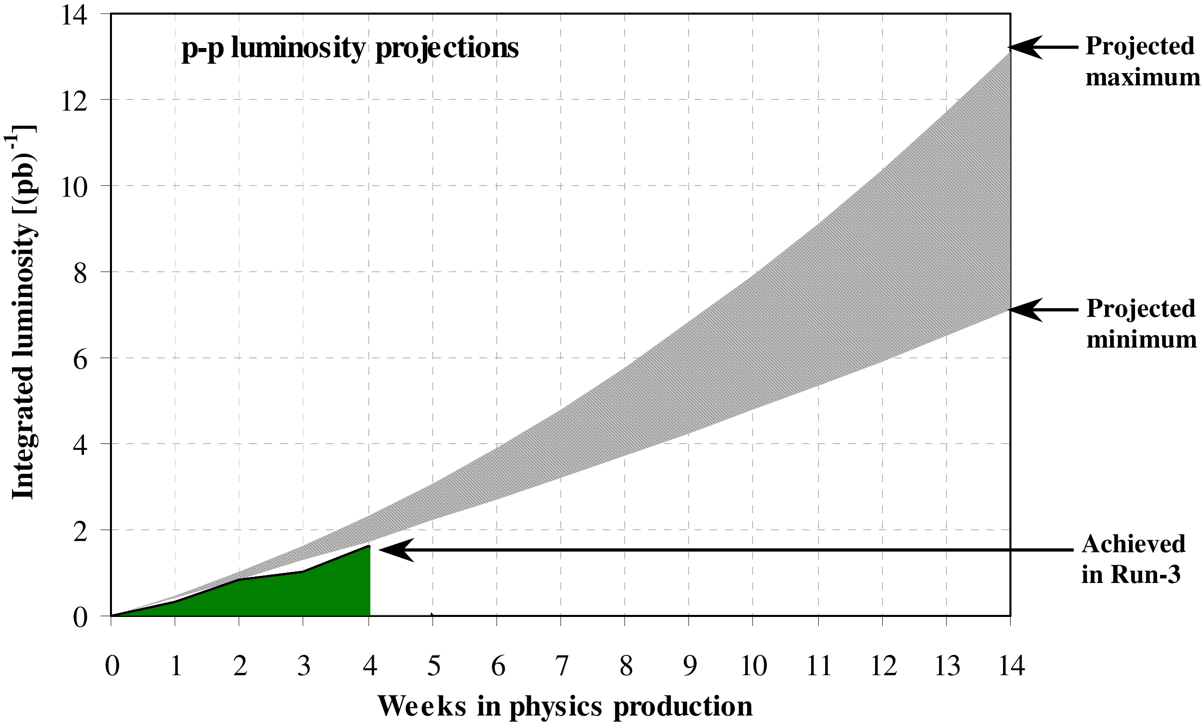

Figure 2: Integrated p-p luminosity achieved in Run-3, and projected minimum and maximum integrated luminosities for p-p collisions, assuming linear weekly luminosity ramp-up in 16 weeks.

Table 3: Projected total integrated luminosities per mode for 1 and 2 modes, assuming linear weekly luminosity ramp-up in 16 weeks.

Mode	Integrated luminosity per mode			
	1 Mode (19 weeks)		2 Modes (7 weeks/mode)	
	Minimum	Maximum	Minimum	Maximum
Au-Au	320 $(\mu b)^{-1}$	895 $(\mu b)^{-1}$	63 $(\mu b)^{-1}$	155 $(\mu b)^{-1}$
$(p\uparrow$-$p\uparrow)$	10 $(pb)^{-1}$	20 $(pb)^{-1}$	3.2 $(pb)^{-1}$	4.8 $(pb)^{-1}$
Si-Si	?	65 $(nb)^{-1}$	?	12 $(nb)^{-1}$

Following are specific comments on the running modes:

Gold on gold – The installation of NEG coated beam pipes is expected to raise the threshold amount of beam that can be accelerated and stored. NEG coated beam pipes near Phobos should also reduce the background at this experiment. A reduction of the experimental background is also expected from a major upgrade in the collimation system, as well as the installation of shielding. Efforts are under way to eliminate the machine maintenance time due to ice formation at power leads, and to improve the reliability of corrector power supplies. A number of software projects will increase the operational efficiency. An extra rf bunch merge in the Booster should lead to a more reliable delivery of high-intensity Au bunches into RHIC.

Polarized protons on polarized protons – With a projected 27 weeks of operations in FY2004, we advocate that at a p-p machine development run with a total length of at least 5 weeks be scheduled. Without such a run we would be at great risk to provide for any increased performance in a likely p-p physics run in FY2005. We are proposing that a possible RHIC p-p run is scheduled later during the RHIC run so that a 4 week AGS polarized proton commissioning run can be completed before a RHIC p-p run would start. A normal conducting helical partial snake, to be installed in the AGS, should increase the polarization at AGS extraction from 40% to 50%. The main goal of the RHIC pp development run would be to commission the new polarized hydrogen jet target and to set-up RHIC with a new betatron tune working point that would allow for increased beam-beam interaction, which limited luminosity during Run-3. A 3-day access period for the installation of the polarized jet target is included in the 5 weeks.

Silicon on silicon – The listing for Si-Si serves as an example of an intermediate heavy ion. Si is easily produced by the injector, and with an equal number of protons and neutrons acceleration in RHIC is the same as for deuterons. The set-up should not be more complicated than for the d-Au run.

Part II – 5-Year Projections

For both Au-Au and p-p the RHIC performance approaches the design parameters (75% of average store luminosity and 50% of weekly integrated luminosity). The 5-year plan laid out below aims at reaching the "enhanced" RHIC performance consisting of a factor of four increased luminosity for Au-Au operation, and an additional factor of four for p-p by doubling the proton bunch intensity, which is possible because of the much reduced effect of intra-beam scattering (IBS).

Below we present 5-year luminosity projections for gold-gold collisions and polarized proton collisions. For simplicity we assume for both modes a set-up period of 5 weeks, and a luminosity production period of 14 weeks in each fiscal year from 2004 to 2008. In our model the weekly luminosity increases linearly in time, beginning after 3 weeks of machine set-up, and reaching a minimum or maximum after 14 week of production.

We take for the minimum weekly luminosity the best weekly luminosity that has been demonstrated in the past. The yearly evolution of the maximum weekly luminosity is based on the assumption that all the improvements outlined below are successful and that a minimum of 5+14 weeks of running in the particular mode is scheduled every year to allow for commissioning of the improvements and development of the machine performance. However, the most likely luminosity evolution is in between these two boundaries. Future updates will change these projections significantly, in particular the minimum projections. Note that running 5+14 weeks of both Au-Au and p-p in a single year requires 41 weeks of cryo-operation. This is only a little more than the nominal 37 weeks. On the other hand, if a single mode is run in a particular year the weekly luminosity after the 5+14-week period is projected to be constant at the values listed in Table 5 and Table 6. In this case the projections for the other mode will need to be extended by one year since the commissioning and performance development did not occur during this year.

Luminosity limitations – A number of effects limit the achievable luminosity. High intensity beams lead to a vacuum breakdown, caused by electron clouds and beam loss driven desorption. This problem may be cured through the installation of NEG coated beam pipes in the warm sections. Intrabeam scattering increases the transverse emittance during stores and causes debunching. Ultimately, electron cooling is required, beyond the 5-year outlook of this note. The beam-beam interaction limits the beam and luminosity lifetime especially for protons. For this reason alternative working points are now under investigation. Furthermore, in proton operation only 2 collisions per turn can be accommodated with high bunch intensities. Instabilities, especially around transition will require a transverse damper in the future. To reduce experimental backgrounds a two-stage collimation system and shielding in the experimental halls is needed. Table 4 lists the main projects to address these and other issues. Some of the listed projects may shift in time or extend further into the future. In addition, new projects will appear, as we better understand the machine limitations.

Operation at energies other than 100 GeV/nucleon – For Au-Au operation at 100 GeV with $\beta^* = 1$ m the limiting aperture is in the triplet. For energies less than 100 GeV the unnormalized beam emittance is larger and, to maintain the beam size within the limiting aperture in the triplet, the β-function in the triplet has to be reduced, which results in a larger β^*. The combined effect is that the luminosity scales with the square of the energy, i.e. at 10 GeV β^* is 10 m and the luminosity is reduced by 100 from its value at 100 GeV.
For p-p operation the luminosity is expected to increase linearly with energies above 100 GeV. Initial operation at 250 GeV requires about 8 weeks of commissioning time for both luminosity and polarization development.

Time in store – In Run-3 the fraction of the time at stores divided by the total time, reached 32% for deuteron-gold collisions and 41% for polarized proton collisions. This can be improved in a number of areas (see Table 4). Time can be gained through the reduction of magnet quenches, the elimination of maintenance time for current leads due to ice ball formation, a more reliable cooling system in the AGS-to-RHIC transfer line, faster down ramps, an improved reliability of the corrector power supplies, better ramp maintenance, and faster machine set-up. Time savings of at least one day per run are possible in each area. We project that the time at store can be increased to about 100 hours per week, or 60%.

5-year projections – In Table 5 luminosities are estimated for gold-gold collisions, assuming a 5+14 week run. For the maximum luminosities quoted in this table, the projects listed in Table 4 need to be completed successfully. Figure 3 shows the total integrated luminosities for the period under consideration.
In Table 6 and Figure 4 the projection for polarized proton collisions are displayed. Table 6 also shows the expected evolution of proton beam polarization for operation at 100 GeV. The main improvements come from increased polarization in the AGS due to the installation of a warm helical partial snake (2004), super-conducting strong partial snake (2005) and a new super-conducting solenoid for the OPPIS source (2007). The benefits of a second super-conducting strong partial snake for the AGS (2007) are also being investigated.

Table 4: Main improvement projects for the RHIC injectors, RHIC luminosity and background, and RHIC time in store.

For FY2004	For FY2005	For FY2006	For FY2007	For FY2008
		RHIC injectors		
Booster low level rf upgrade			New OPPIS solenoid	EBIS test
AGS warm helical snake	AGS cold helical snake		2nd AGS cold helical snake?	
		RHIC luminosity and background		
Collimation system, 1st half	Collimation system, 2nd half			
Shielding PHENIX	Shielding STAR			
Shielding BRAHMS	Shielding PHOBOS			
NEG pipe test (60 m)	NEG pipes (300 m)	NEG pipes (400 m)		
	Solenoids?	Solenoids?		
Dedicated Landau cavities	Transverse damper system			
½ of BPM electronics to alcoves	All BPM electronics to alcoves			
	1 alcove outside ring	2 alcoves outside ring	2 alcoves outside ring	2 alcoves outside ring
Stochastic cooling 1st test	Stochastic cooling 2nd test	Stochastic cooling		
		RHIC time in store		
Orbit feed forward (ramp)	Orbit feed forward (ramp)			
Decoupling (ramp and store)	Decoupling (ramp and store)			
Gradient error correction	Gradient error correction			
AtR cooling	Tune feedback (ramp)			
Current lead ice balls elimination	Chromaticity feedback (ramp)			
Corrector PS reliability	Injection set-up			
Gap cleaning				
Abort kicker pre-fires				
Faster down-ramps				

Table 5: Projected RHIC Au-Au luminosities.

Fiscal year		2002A	2004E	2005E	2006E	2007E	2008E
No of bunches	…	55	56	70	80	90	112
Ions/bunch, initial	10^9	0.7	0.9	1.0	1.0	1.0	1.0
Average beam current/ring	mA	38	49	69	79	89	114
β*	m	1	1	1	1	1	1
Peak luminosity	10^{26} cm^{-2}s^{-1}	5	12	19	21	24	32
Average store luminosity	10^{26} cm^{-2}s^{-1}	1.5	2.9	4.7	5.3	6.0	8.0
Time in store	%	25	40	45	50	55	60
Maximum luminosity/week	$(\mu b)^{-1}$	25	70	127	161	199	290
Minimum luminosity/week	$(\mu b)^{-1}$		25	25	25	25	25
Maximum integrated luminosity	$(\mu b)^{-1}$	89	580	1050	1340	1660	2410
Minimum integrated luminosity	$(\mu b)^{-1}$		210	210	210	210	210

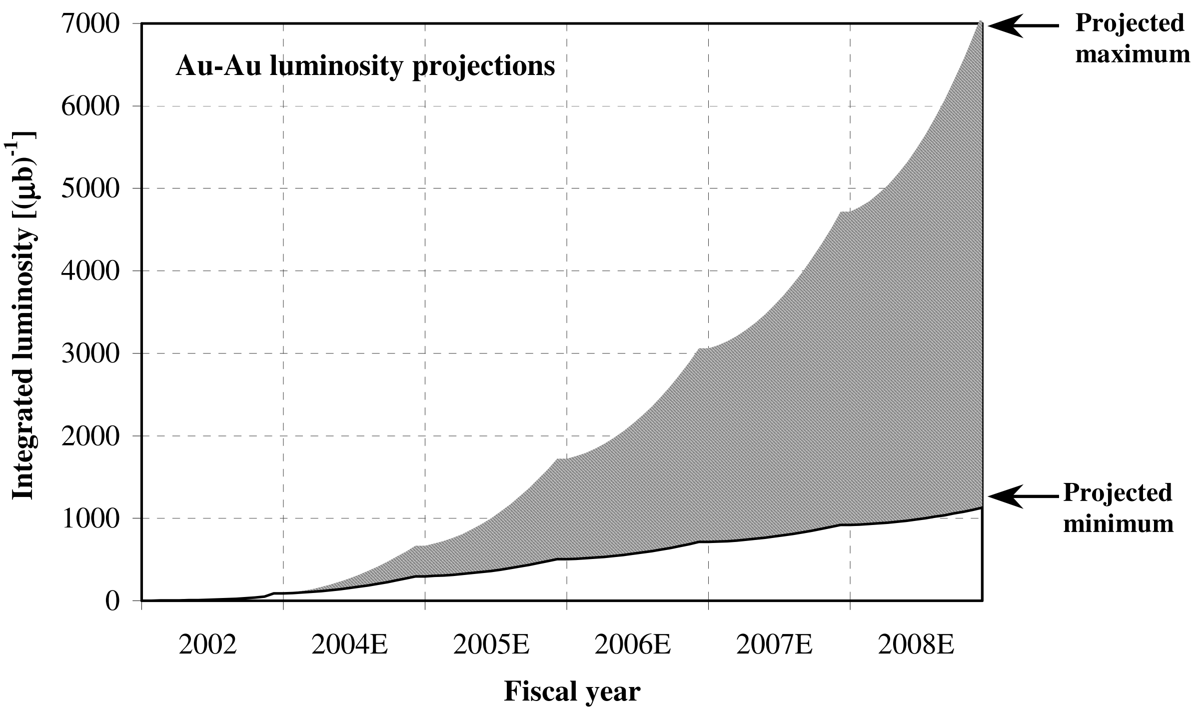

Figure 3: Minimum and maximum projected integrated luminosity for Au-Au collisions.

Table 6: Projected RHIC p-p luminosities.

Fiscal year		2002A	2003A	2004E	2005E	2006E	2007E	2008E
No of bunches	…	55	55	56	56	56	90	112
Ions/bunch, initial	10^{11}	0.7	0.7	1.0	1.4	2.0	2.0	2.0
Average beam current/ring	mA	48	48	70	98	140	225	280
β*	m	3	1	1	1	1	1	1
Peak luminosity	10^{30} cm^{-2}s^{-1}	2	6	11	22	45	72	89
Average store luminosity	10^{30} cm^{-2}s^{-1}	1.5	3	6	13	32	57	72
Time in store	…	30	41	40	45	50	55	60
Maximum luminosity/week	(pb)$^{-1}$	0.2	0.6	1.4	3.5	10	19	26
Minimum luminosity/week	(pb)$^{-1}$			0.6	0.6	0.6	0.6	0.6
Maximum integrated luminosity	(pb)$^{-1}$	0.5	1.6	12	30	84	165	224
Minimum integrated luminosity	(pb)$^{-1}$			5	5	5	5	5
AGS polarization at extraction	%	35	45	55	65	75	80	80
RHIC store polarization, peak	%	25	35	45	60	70	75	75
RHIC store polarization, average	%	15	30	40	55	65	70	70

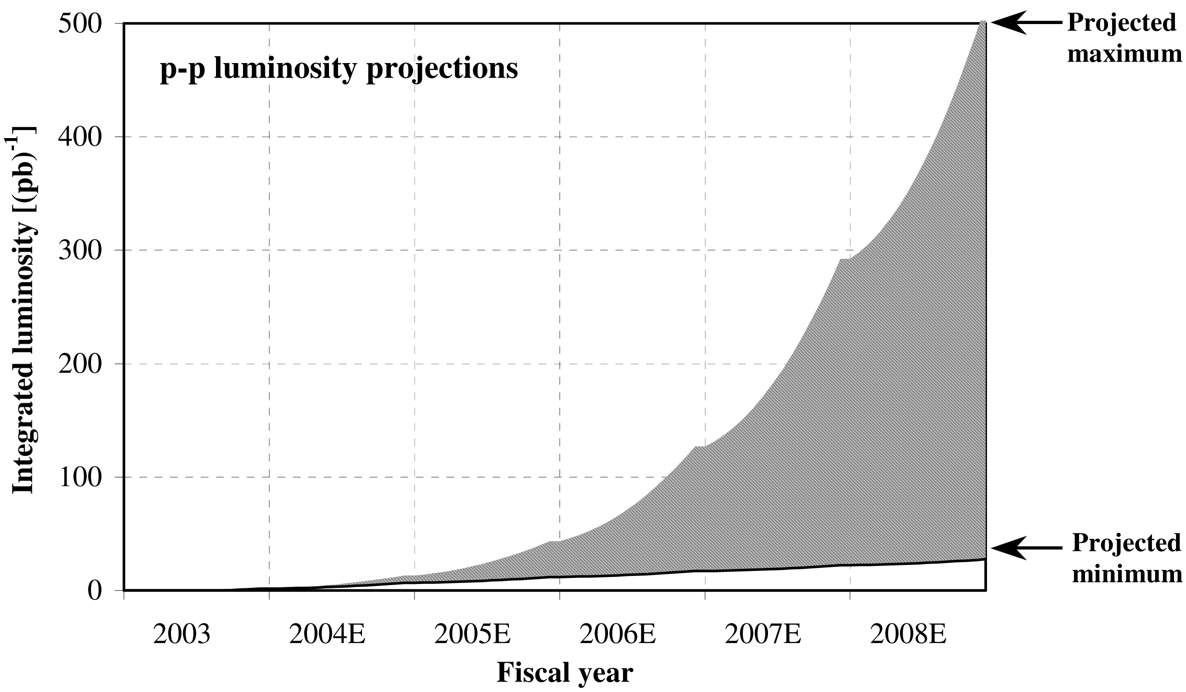

Figure 4: Minimum and maximum projected integrated luminosity for p-p collisions.