PHENIX Beam Use Proposal for RHIC Runs 4-8

The PHENIX Collaboration

03-Sep-03

Abstract

This document summarizes the request from the PHENIX Collaboration for beam species and energies for RHIC Run-4 through Run-8. Scenarios are developed for both 27 and 37 weeks of cryogenic operations per year. Information on the current status of the experiment, on the data sets recorded to date, and the program of proposed upgrades is also provided. The inescapable conclusion of this exercise is that a long-term schedule with only 27 weeks per year of operations greatly restricts the scientific output of RHIC. Conversely, incremental additions to the number of operating weeks per year are hugely leveraged, and must be pursued to provide a timely realization of the scientific output of the program.

Executive Summary

The PHENIX Collaboration proposes a continued program of exploration based on the development of the highest possible luminosities in ion-ion, "proton"-nucleus and polarized proton collisions. Based on the successes of Runs 1-3, the requested running conditions are designed to maximize the discovery potential at RHIC via extended measurement of rare probes and hard processes in various systems, with an emphasis in Runs 5-8 on mapping the dependence of these phenomena versus system size and beam energy. An intensive program of luminosity and polarization development is requested for polarized protons, leading to quality measurements of ΔG in various production channels.

1 Introduction

The PHENIX goals for future RHIC running remain unchanged from those described in our previous submissions to the Program Advisory Committee[1, 2, 3, 4, 5]. Briefly stated, PHENIX has consistently requested Au+Au collisions at the highest possible energy, polarized proton collisions, and proton or deuteron collisions on Au all at the same per nucleon energy, with integrated luminosities sufficient to measure systematic trends in the production of the J/ψ . The cross section for charmonium production is sufficiently small that such integrated luminosities also provide superb results for single particle hadron yields to very high transverse momenta, thereby significantly extending the systematic studies of the suppression patterns measured in RHIC Run-1 (Ref. [10]), Run-2 (Ref. [20]) and Run-3 (Ref. [27]).

1.1 History and Status of the PHENIX Experiment

The PHENIX detector has evolved from a partial implementation of the central arms in Run-1 to a completed installation of the baseline + AEE systems for Run-3. Each of the configurations used for Runs 1-3 was capable of using the delivered luminosity from RHIC to explore both heavy ions (Runs 1 and 2), polarized proton collisions (Runs 2 and 3) and deuteron+Au collisions (Run 3).

The Run-1 data set of $\sim 1\ \mu b^{-1}$ Au-Au at $\sqrt{s_{NN}} = 130$ GeV was obtained with a partially instrumented subset of the PHENIX Central Arms, as shown in Figure 1. In Run-2, $\sim 24\ \mu b^{-1}$ of Au-Au at $\sqrt{s_{NN}} = 200$ GeV and $\sim 130\ nb^{-1}$ of polarized proton data at 200 GeV were recorded. The detector configuration, data acquisition and triggers were significantly upgraded in Run-2. All central arm detectors were read out, and the South Muon Arm was installed (Figure 2). The complete PHENIX experiment (Figure 3), which was available for Run-3, was used to measure 2.7 nb^{-1} of d+Au collisions and 0.35 pb^{-1} of polarized p+p collisions. In fact, three additional "beyond the baseline" components were also installed for Run-3:

1. The Zero-Degree Calorimeters were augmented by a Shower-Max Detector (SMD), which was of crucial importance in providing local polarimetry capabilities during the commissioning of the spin rotators at IP8.
2. Two Forward Calorimeters (FCAL's) were installed to provide event characterization for d+Au collisions.
3. A New Trigger Counter (NTC) was used during p+p running to extend the fraction of minimum bias cross section accessible to the PHENIX Level-1 trigger system.

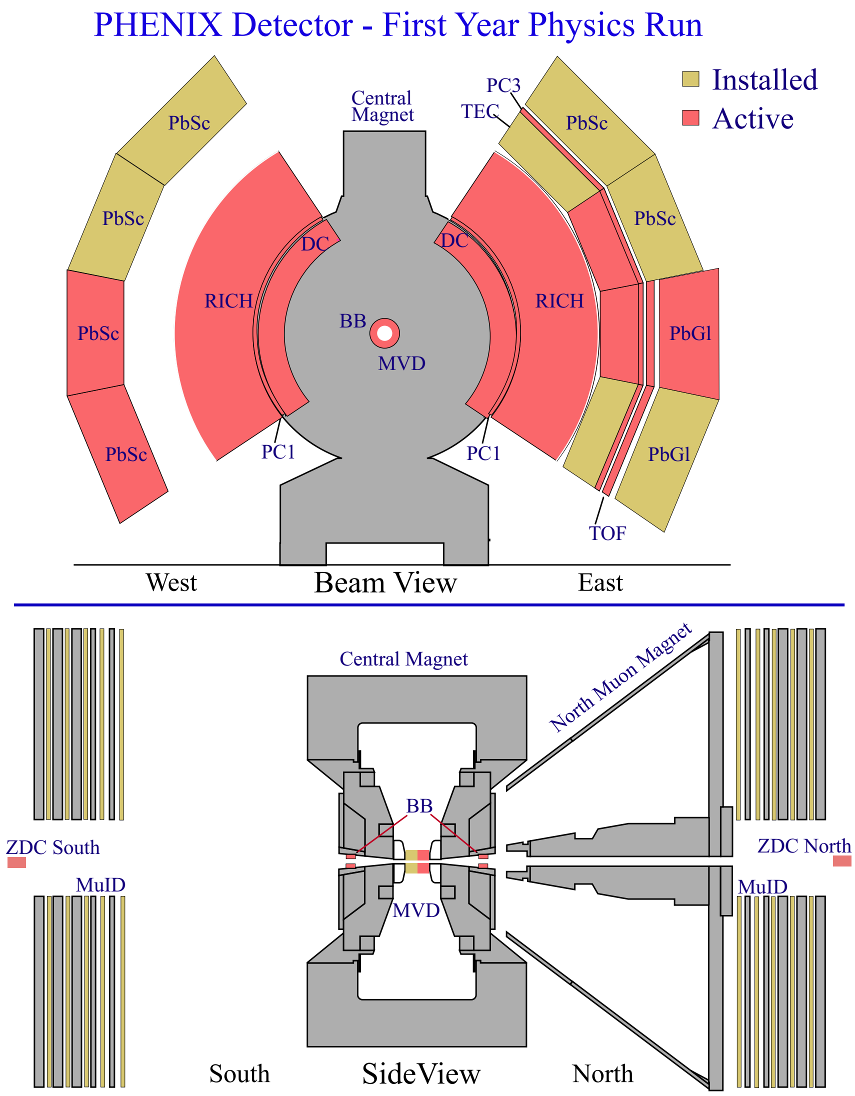

Figure 1: Installed and active detectors for the RHIC Run-1 configuration of the PHENIX experiment.

For Run-4, the capabilities of the PHENIX central spectrometer will be significantly extended through the addition of an Aerogel Cerenkov Counter (ACC). This detector, consisting of 160 elements of hydrophobic aerogel installed in the West arm of PHENIX(Figure 5), will provide the additional particle identification capabilities illustrated in Figure 4, which will permit a crucial test of quark recombination models[6, 7] for $p_T > 5$ GeV/c.

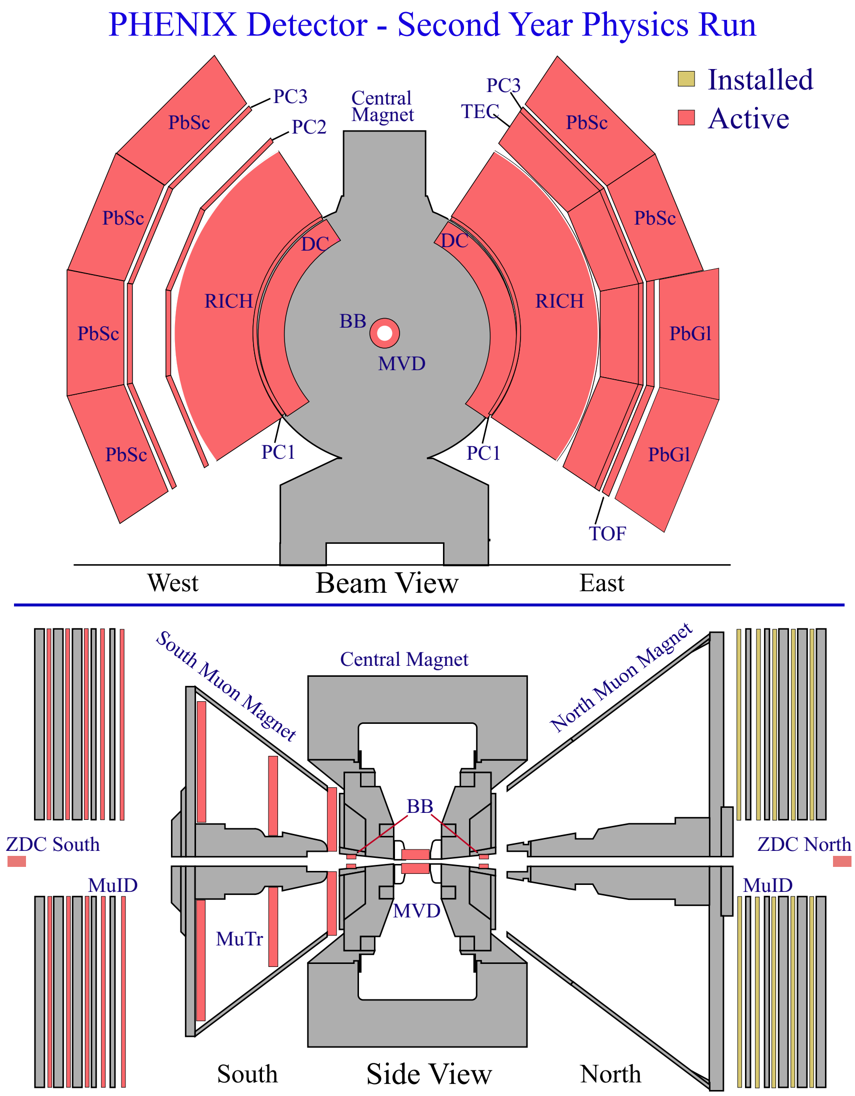

Figure 2: RHIC Run-2 configuration of the PHENIX experiment.

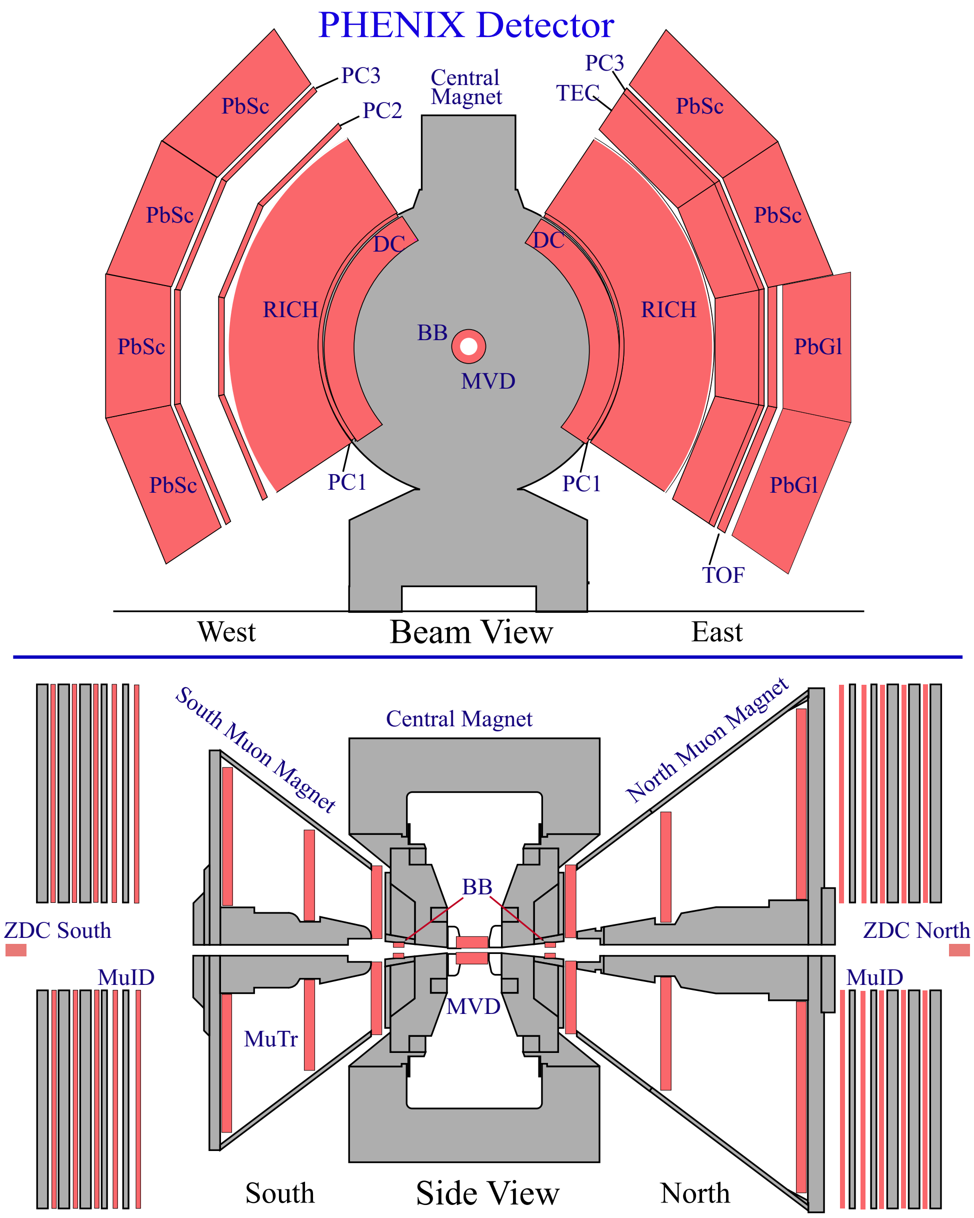

Figure 3: RHIC Run-3 configuration of the PHENIX experiment.

		Pion-Kaon separation	Kaon-Proton separation
TOF	σ~100 ps	0 - 2.5	- 5
RICH	n=1.00044 γth~34	5 - 17	17 -
Aerogel	n=1.01 γth~8.5	1 - 5	5 - 9

Figure 4: Hadron identification in the PHENIX Central Arms with the Aerogel Cerenkov Counter system.

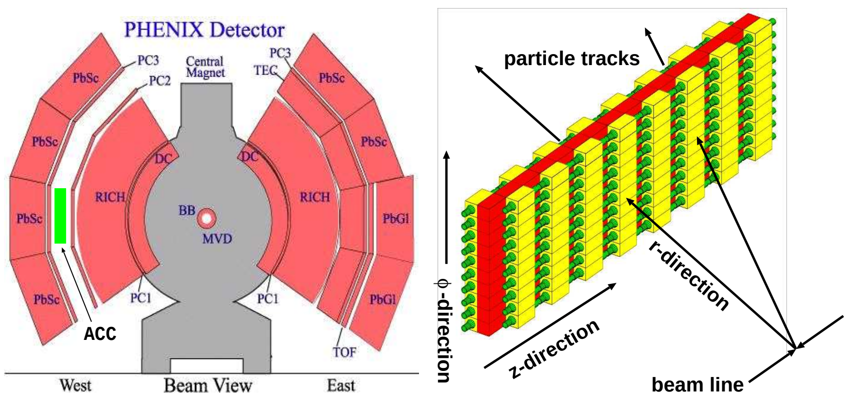

Figure 5: The aerogel detector in the west arm between pad chamber 2 (PC2) and 3 (PC3) in the W1 sector (left) and the aerogel detector structure and orientation with respect to the beam line (right) are shown.

1.2 Status of PHENIX Physics

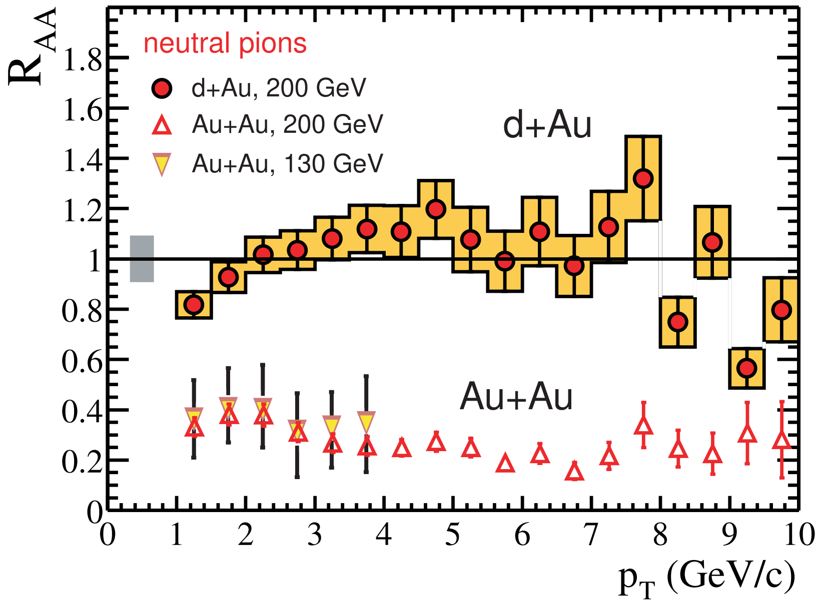

Figure 6: The suppression factor R_{AA} measured for π^0 production by PHENIX in Run-1 130 GeV Au+Au collisions[10], Run-2 200 GeV Au+Au collisions[20], and Run-3 200 GeV d+Au collisions[27].

The published results from Run-1 Au-Au collisions[8]-[19], from Run-2 Au-Au collisions at 200 GeV[20]-[23] and Run-2 proton-proton collisions[24, 25], and Run-3 d+Au collisions[27] clearly demonstrate that PHENIX has the capability to make high quality measurements in both hadronic and leptonic channels for collisions ranging from p+p to Au+Au. Together these 19 publications encompass physics from the barn to picobarn level; their very breadth precludes a detailed presentation here. Instead, we will provide a few results representative of the PHENIX program in rare probes, as it is these channels that determine the thrust and scope of our beam request. The discussion will focus on yields per integrated luminosity rather than on physics content; for that one should refer to the cited publications.

The range of transverse momenta accessible from Runs 1-3 is illustrated in Figure 6, which shows the suppression pattern of π^0's produced at y=0 in Au+Au collisions at 130 GeV (Run-1) and 200 GeV (Run-2), together with 200 GeV d+Au results (Run-3). Implicit in this result is the corresponding yield in 200 GeV p+p collisions, shown as a transverse momentum spectrum in Figure 7. These results are indicative of the PHENIX reach in transverse momentum for parton-parton integrated luminosities equivalent to 0.1-1.0 pb^{-1} in proton+proton collisions.

PHENIX has also obtained a first measurement of J/ψ production in p+p collisions at 200 GeV[25], shown in Figure 8. Both the mean transverse momentum and the total

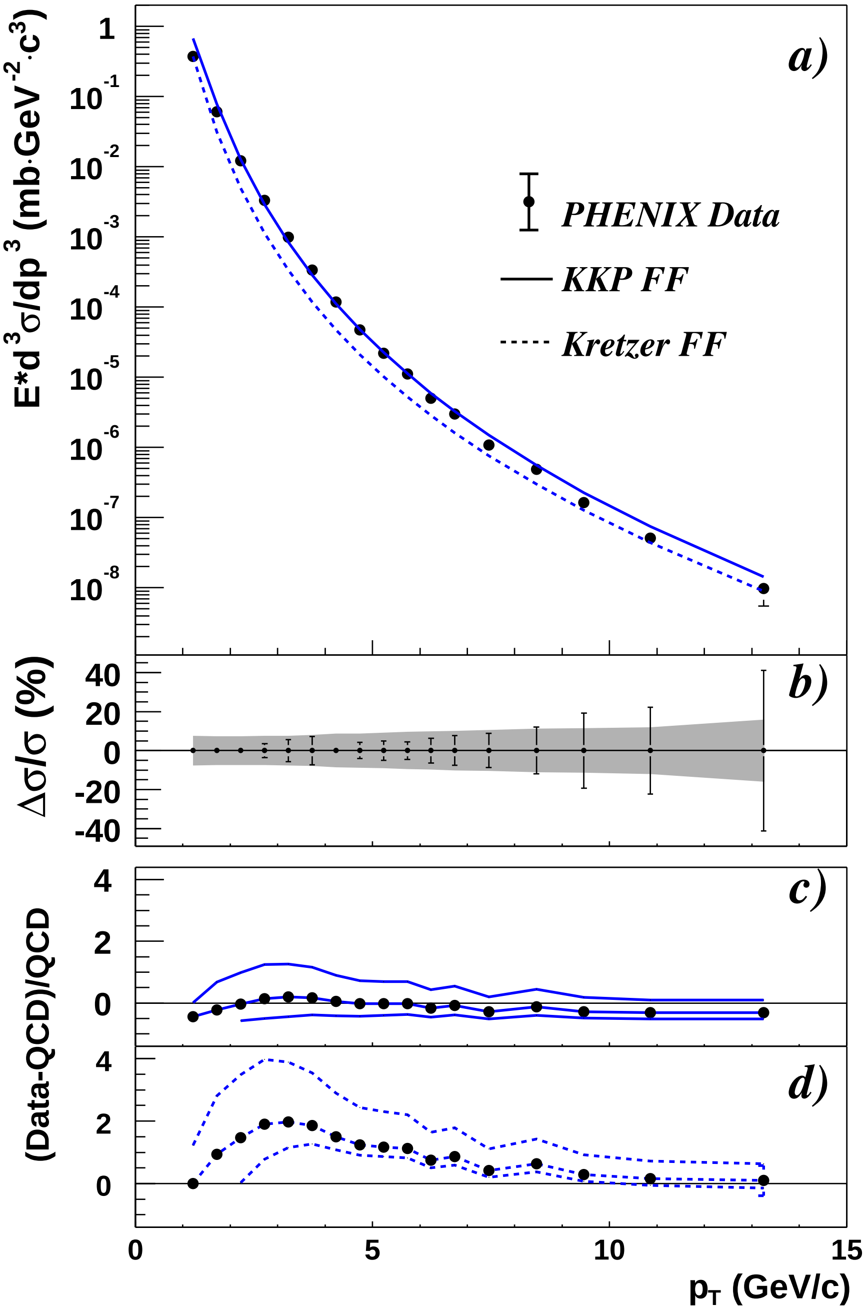

Figure 7: The cross section for $p + p \rightarrow \pi^0 + X$ measured by PHENIX in 200 GeV p+p collisions at y=0. For details, consult Ref. [24].

cross section are in reasonable agreement with trends established in lower-energy proton+proton collisions. The measurement of the yield down to very low values of the transverse momentum is a particular strength of the PHENIX apparatus. However, both the actual p_T spectrum and the values of dn/dy inferred from it are severely limited by the available integrated luminosity ($<\sim$0.1 pb^{-1}) of this Run-2 measurement, as seen in

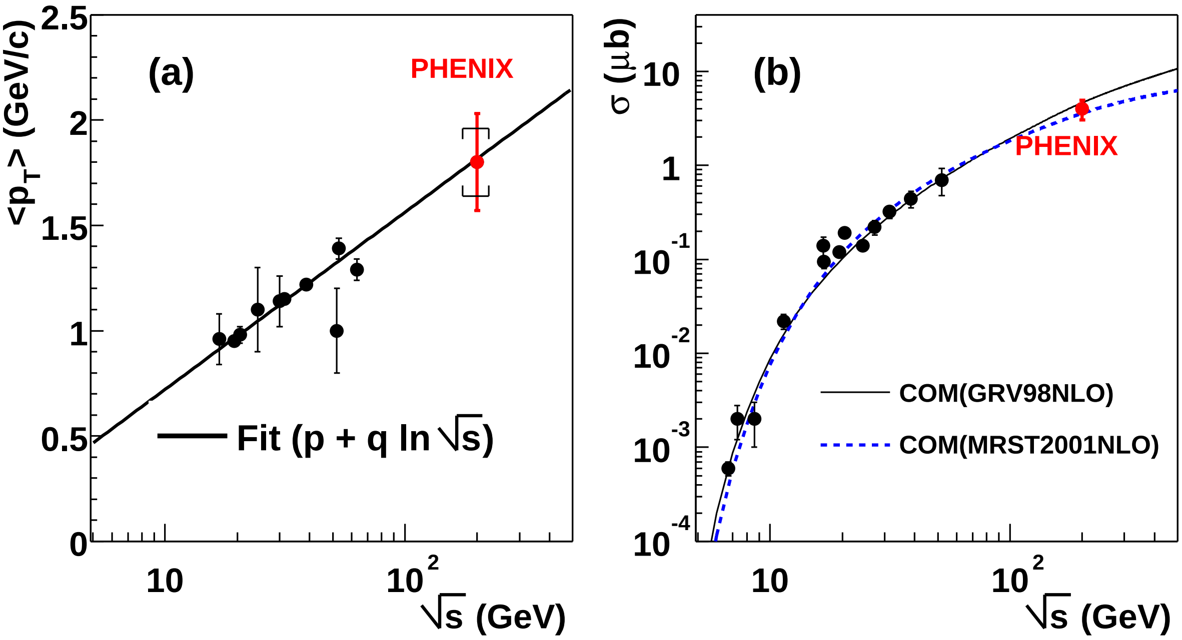

Figure 8: The mean transverse momentum and total cross section for J/ψ 's produced in in 200 GeV p+p collisions. For details, consult Ref. [25].

Figure 9. It is clear that data sets of order 10-100 larger will be necessary to completely characterize J/ψ production at RHIC. To exploit the potential of this channel for measurement of ΔG in polarized proton+proton collisions will require an additional factor of 10 in integrated luminosity.

It is instructive to use these recent results both as a predictor of the program proposed here (see Section 3 and as a measure of progress towards the goals stated by PHENIX over a decade ago in the PHENIX Conceptual Design Report. Table 1, taken directly from the "Physics Goals" section of that report, outlines the full range of physics observables anticipated in 1993. The broad program of measurements foreseen in that document has held up remarkably well during the initial phase of RHIC operations. To date, PHENIX has produced (or is preparing) publications on all of the channels found under "Global" and "Charged Hadrons" categories, on perhaps half of those in the "Photon" section, and on only small subset of the e^+e^-, $\mu^+\mu^-$ and $e\mu$ categories. In some cases (e.g., continuum di-leptons), the principle obstacle has been backgrounds, which are being aggressively addressed via our proposed upgrades. More typically, the issue has been one of integrated luminosity. In the discussion that follows, the "onium" states, in particular J/ψ , will be used as an indicator of sensitivity to the rare processes which will produce detailed insights into the dense matter being produced in RHIC collisions.

Table 1: PHENIX Physics Goals from Conceptual Design Report (1993)

Quantity to be Measured	Category*	Physics Objective
e^+e^-, $\mu^+\mu^-$		
• $\rho \to \mu^+\mu^-/\rho \to \pi\pi$, $d\sigma/dp_\perp$	BCD	Basic dynamics (T, τ, etc.,) for a hot gas,
$\omega \to e^+e^-/\omega \to \pi\pi$, $d\sigma/dp_\perp$		transverse flow, etc.
• ϕ-meson's width and $m_{\phi\to e^+e^-}$	QGP	Mass shift due to chiral transition (C.T.) [29]
$\phi \to e^+e^-/\phi \to K^+K^-$	QGP	Branching ratio change due to C.T. [30]
ϕ-meson yield (e^+e^-)	ES	Strangeness production ($gg \to s\bar{s}$)
• $J/\psi \to e^+e^-, \mu^+\mu^-$	QGP, QCD	Yield suppression and the distortion
$\psi' \to \mu^+\mu^-$		of p_T spectra due to Debye screening
$\Upsilon, \to \mu^+\mu^-$		in deconfinement transition (D.T.) [31]
• $1 < m_T(l^+l^-) < 3$ GeV	ES, QGP	Thermal radiation of hot gas, and
(rate and shape)		effects of QGP [32, 33, 34]
• $m_{l^+l^-} > 3$ GeV $\to \mu^+\mu^-$	QCD	A-dependence of Drell-Yan, and
	QGP	thermal $\mu^+\mu^-$ [32, 33, 34, 35]
• $\sigma \to \pi\pi, e^+e^-, \gamma\gamma$	QGP	Mass shift, narrow width due to C.T. [29]
$e\mu$ coincidence		
• $e\mu$, $e(p_T > 1$ GeV/c)	QCD, QGP	$c\bar{c}$ background, charm cross section [36]
Photons		
• $0.5 < p_T < 3$ GeV/c γ	ES, QGP	Thermal radiation of hot gas, and
(rate and shape)		effect of QGP [33, 34]
• $p_T > 3$ GeV/c γ	QCD	A-dependence of QCD γ
• π^0, η spectroscopy	BCD	Basic dynamics of hot gas, strangeness in η
• $N(\pi^0)/N(\pi^+ + \pi^-)$ fluctuations	QGP	Isospin correlations and fluctuations [37, 38]
• High p_T π^0, η from jet	QGP	Reduced dE/dx of quarks in QGP [39]
Charged Hadrons		
• p_T spectra for $\pi^\pm$, $K^\pm$, p, $\bar{p}$	BCD	Basic dynamics, flow, T, baryon density,
		stopping power, etc.
	QGP	Possible second rise of $< p_T >$ [40]
• $\phi \to K^+K^-$	ES, QGP	Branching ratio, mass width [30, 41]
• K/π ratios	ES	Strangeness production
• $\pi\pi$ + KK HBT	BCD	Evolution of the collision, $R_\perp$
	QGP	Long hadronization time ($R_{\rm out} \gg R_{\rm side}$) [42]
• Antinuclei	QGP	High baryon susceptibility due to C.T.? [43]
• high p_T hadrons from jet	QGP	Reduced dE/dx of quarks in QGP [39]
Global		
• $N_{\rm tot}$ (total multiplicity)	BCD	Centrality of the collision
• $dN/d\eta, d^2N/d\eta d\phi, dE_T/d\eta$	BCD	Local energy density, entropy
	QGP	Fluctuations, droplet sizes [44]

* BCD = Basic collisions dynamics. ES = Thermodynamics at early stages.
QGP = Effect of QGP phase transition. QCD = Study of basic QCD processes.

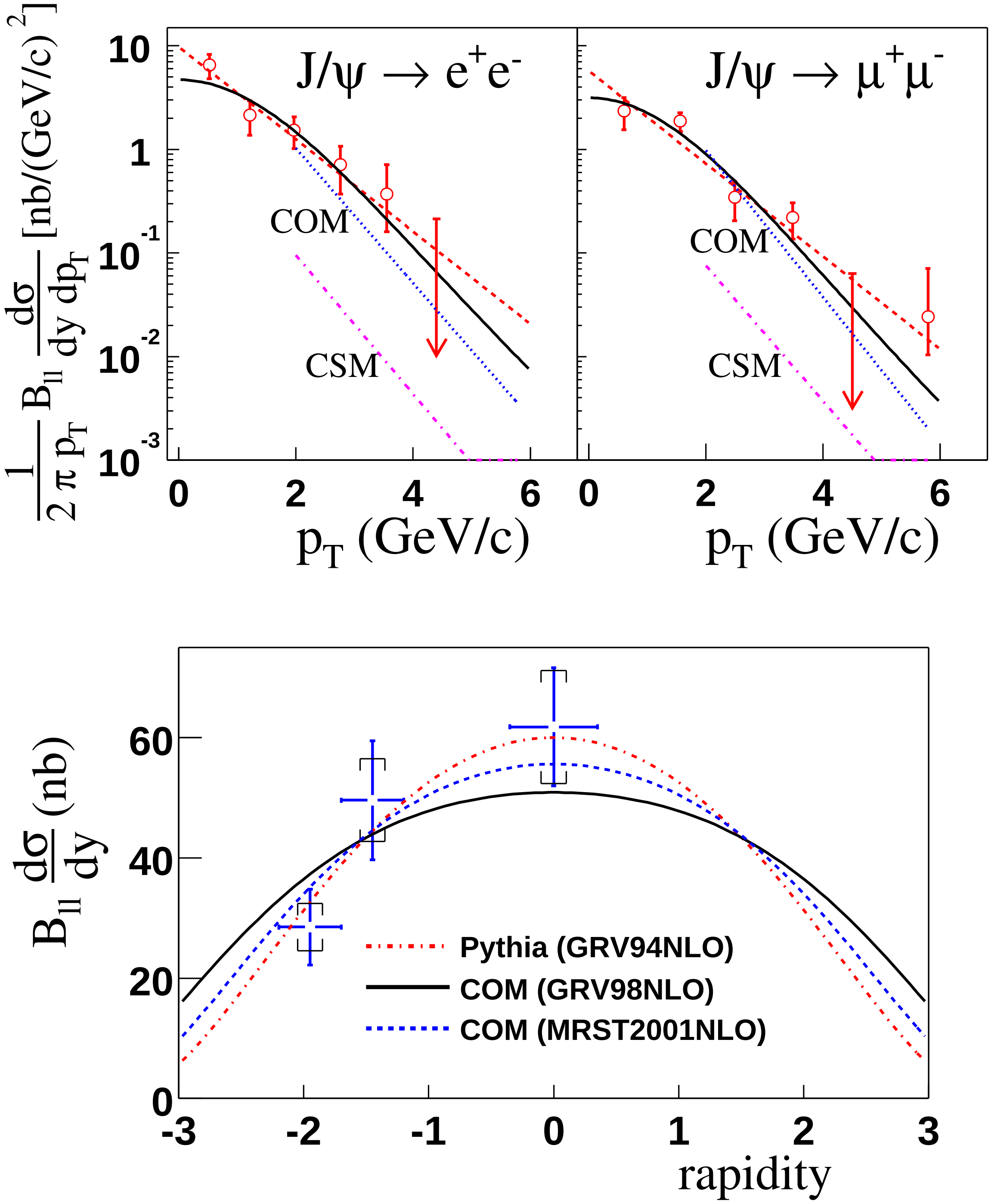

Figure 9: The transverse momentum spectrum (top) and the dn/dy distribution (bottom) for J/ψ 's produced in in 200 GeV p+p collisions. For details, consult Ref. [25].

2 Run Planning Assumptions and Methodology

2.1 ALD Input

In response to the outcome from the Jul-03 DOE Review of the RHIC Program, the call for Beam Use Proposals was modified on 23-Jul-03 to be responsive to the request for a "detailed and integrated 5-year planning effort". The boundary conditions included:

1. A time span covering FY04-FY08, corresponding to RHIC Runs 4 through 8.
2. Luminosity according to Collider-Accelerator Department guidance, specifying anticipated developments over the five-year period.
3. Two scenarios:
    - A "constant effort" scenario corresponding to 27 weeks per year of cryogenic operations.
    - An "Optimum" scenario defined as 37 weeks of cryogenic operations per year.

2.2 CAD input

Detailed guidance was provided by the Collider-Accelerator Department (updated on 08-Aug-03) describing the projected year-by-year luminosities for various species, along with the expected time-development of luminosity in a given running period[63]. Here we briefly summarize the parameters most relevant to our planning process:

2.2.1 Overheads

- **Cooldown**: 2 weeks
- **Warm-up**: 1 week
- **Set-up**: 2 weeks ≡ time required to set-up machine for a given species.
- **Ramp-up**: 3 weeks ≡ time required to achieve stable operations with useful (initial) luminosities.

Thus, 27 weeks of cryo operations translates into 27 - 2 - (2+3) - 1 = 19 weeks of stable operations for physics. Running a second species during a given year invokes a second (2+3) weeks of set-up + ramp-up.

2.2.2 Luminosity Development

Whenever possible, minimum projected luminosities were obtained from previously achieved operating conditions. Maximum projected luminosities were also provided, based on current understanding of the accelerator limits. In both cases, a "16 week linear growth" model was applied to model the time development of the initial luminosity value achieved at the end of "ramp-up" to the final value. This model, based on experience from Runs 1-3, obviously sets a premium on extended single-species running. This is presented in Table 3 of Ref. [63], which shows a penalty factor in integrated luminosity ranging from 3 to 5 for two-mode versus single-mode running. Guidance was also provided for anticipated year-by-year of the maximum luminosity which would result from various planned improvements in accelerator operations.

2.2.3 Polarized Protons

An amendment to the CAD guidance was provided on 22-Aug-03 strongly advocating a spin development period in Run-4. Since this was an important input to the PHENIX planning process, we quote it here in its entirety:

> 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 p+p 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.

2.3 PHENIX Input

The charge to produce a detailed Beam Use Proposal addressing both 27 and 37 week scenarios, while daunting, has proved an instructive exercise which compelled the collaboration to examine its physics goals and priorities. What has emerged, after investigation of numerous scenarios, is a re-affirmation of the program proposed in last year's Beam

Use Proposal[5], coupled with an extension of that program to include Runs 6, 7 and 8. Specifically, the following measurements were identified as compelling:

- Au+Au at 200 GeV with sufficient integrated luminosity to provide a definitive measurement of J/ψ production in heavy ion collisions at RHIC.
- Si+Si at 200 GeV, to examine both J/ψ production and jet production and (perhaps) quenching in a lighter system.
- Au+Au at 62.4 GeV to investigate the energy dependence of the high p_T suppression pattern observed at 200 GeV.
- Continued development of polarized proton luminosity and polarization leading to a sensitive measurement of the gluon polarization of the proton via 200 (and 500) GeV p+p collisions.

The constraints imposed by the necessary time to develop luminosity, set-up times, and the restriction to 27 weeks cryo weeks per year (even, to some extent, 37 weeks) are so severe that it is not possible to accommodate many otherwise useful measurements (d+Au at a lower energy, d+Si at 200 GeV, energy scans, other species) within the scope of this proposal.

To examine the complex trade-offs required to optimize the physics output of the PHENIX experiment, we have developed a spreadsheet that incorporates the CAD guidance for projected luminosity and its year-by-year expected growth. (A sample output appears near the end of this document in Figure 13; the actual spreadsheet is available at the URL given in Ref. [64].) To quantify the expected physics for a given integrated luminosity, three characteristic measurements were identified: The number of J/ψ 's measured in the North Muon Arm, the p_T reach for π^0's in the central arms, and the reach in p_T for A_{LL} measured via π^0's (again, in the central arms). The calibration of these figures-of-merit using existing data, and their extension to other systems via simple scaling relations are detailed in the remainder of this section. The sensitivity of other rare probes and to various physics scenarios will be presented, together with the actual beam use request, in Section 3.

2.3.1 J/ψ yields

Preliminary analysis of J/ψ 's observed in the North Muon Arm for Run-3 (200 GeV) p+p collisions establishes a yield of roughly 1600 per pb^{-1}. The energy dependence of the yield uses a modification of the Schuler parameterization[65]:

$$\sigma(\sqrt{s})_{J/\psi} \sim \sqrt{s}(1 - \frac{M_{J/\psi}}{\sqrt{s}})^{12} \quad ,$$

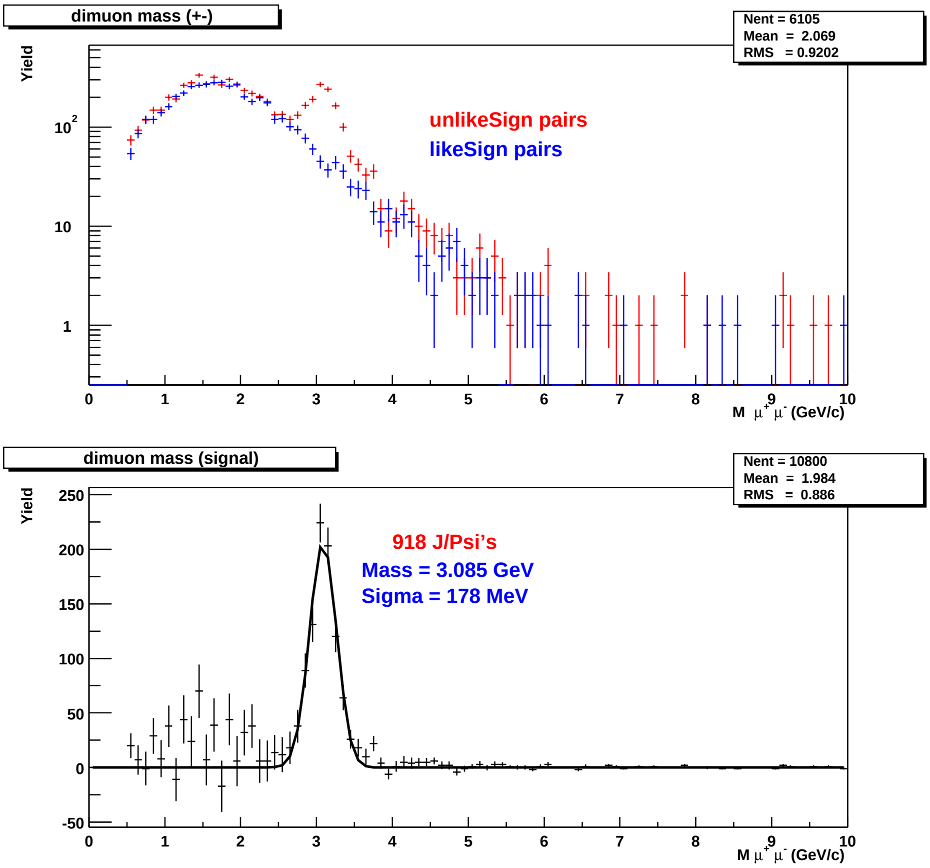

Figure 10: The invariant mass distribution of muon pairs in the PHENIX North Muon Arm for 200 GeV d+Au collisions.

which provides an adequate description of the variation in total cross section with energy shown in Figure 8 in the RHIC energy regime. For A+A collisions, the yield is scaled assuming "normal nuclear suppression", i.e., $A^{\alpha} \cdot A^{\alpha}$ with $\alpha = 0.92$; for d+A the corresponding scaling is assumed to be $2 \cdot A^{\alpha}$. This scaling procedure has been verified when using the p+p Run-3 data to predict the ~ 900 J/ψ 's observed in the North Arm d+Au sample[1], as shown in Figure 10. An empirical multiplicity-dependent tracking efficiency is applied, again determined via existing data. To calibrate the number of North Arm J/ψ 's in the following tabulations relative to a physics measurement, note that the results in Ref. [25] and shown in Figures 8 and 9 were obtained with a signal of $78 - 13 = 65 \pm 9.5$ muons.

[1]This is a semi-quantitative calibration only and should not be interpreted as a physics statement regarding the value of α!

2.3.2 High p_T π^0's

The figure of merit here is the p_T bin in which the cross section $Ed^3\sigma/dp^3$ is measured with a statistical accuracy of 20%. The calibration is obtained from the measured results from Run-2 p+p collisions, which measured the yield at $p_T = 10$ GeV/c with a statistical accuracy of 20% using ~ 0.04 pb^{-1} of triggered data. This result is scaled to other energies using x_T scaling, as reported by PHENIX in Ref. [26], using the functional form

$$\frac{Ed^3\sigma}{dp^3} \sim \frac{1}{(\sqrt{s})^n} \cdot \frac{1}{x_T^m}$$

with $m = 9.30$, $n = 6.33$. This choice of parameters was verified to give a reasonable description over the range 40 GeV $< \sqrt{s} <$ 540 GeV. The yield for A+B collisions is scaled as A·B, i.e. assuming neither Cronin enhancements nor nuclear suppression.

2.3.3 $A_{LL}(\pi^0)$

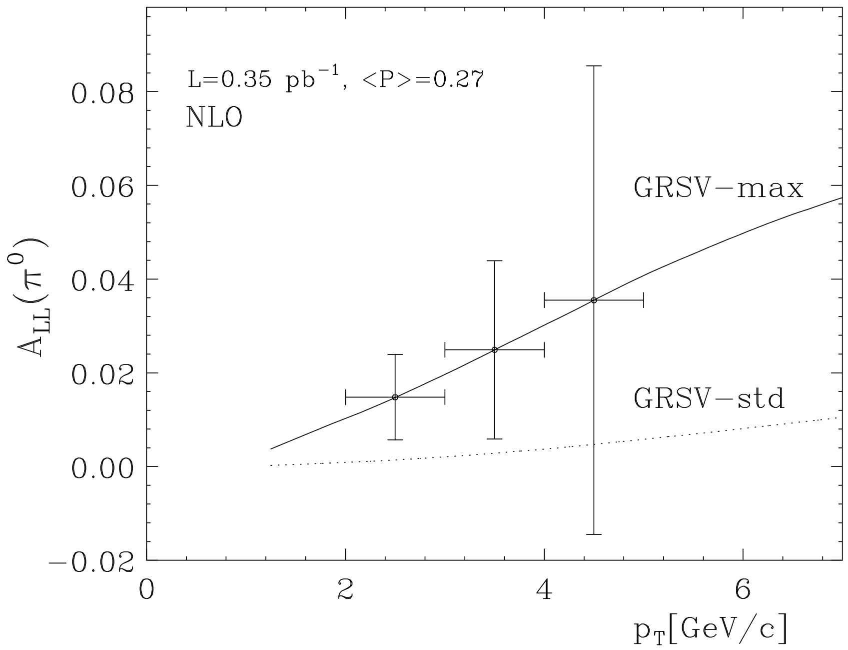

Figure 11: The projected statistical sensitivity to A_{LL} via $p + p \rightarrow \pi^0 + X$ at 200 GeV for 0.35 pb^{-1} and an average longitudinal polarization of 27%.

The first measurement by PHENIX of A_{LL} will be via the π^0 channel, with an expected sensitivity as shown in Figure 11. The p_T reach of this measurement is taken as the figure of merit for polarized proton running. The statistical significance is scaled as $\mathcal{P}^4 \int \mathcal{L} \cdot dt$, where $\mathcal{P}$ is the longitudinal polarization and $\int \mathcal{L} \cdot dt$ is the integrated luminosity. The underlying distribution of π^0's yields which is responsible for the rapid increase in the error with transverse momentum is scaled using the methods described in the previous section.

3 Beam Use Proposal for Runs 4-8

3.1 Executive Summary

A summary of the proposed species, energies and running times for RHIC Runs 4 through 8 are presented in Table 2 (27 week scenario) and Table 3 (37 week scenario), along with the expected integrated luminosities and equivalent p+p value (calculated via binary scaling, i.e., for $A+B$ reactions, $\mathcal{L}dt|_{equiv} = (A \cdot B)\ \mathcal{L}dt$).

Table 2: The PHENIX Beam Use Proposal for 27 cryo weeks per year

RUN	SPECIES	$\sqrt{s_{NN}}$ (GeV)	PHYSICS WEEKS	$\int \mathcal{L}dt$ (delivered)	p+p Equivalent
4	Au+Au p+p	200 200	14 (5 development)	316 μb^{-1} -	12.3 pb^{-1}
5	Si+Si p+p	200 200	9 5	5.5 nb^{-1} 3.0 pb^{-1}	4.3 pb^{-1} 3.0 pb^{-1}
6	Au+Au	62.4	19	117 μb^{-1}	4.3 pb^{-1}
7	p+p	200	19	158 pb^{-1}	158 pb^{-1}
8	Au+Au	200	19	2157μb^{-1}	84 pb^{-1}
9	p+p	500	19	540 pb^{-1}	540 pb^{-1}
10	d+Au	62.4	19	3.3 nb^{-1}	1.3 pb^{-1}

For planning purposes, and to avoid "end effects" on the five-year interval, it was found useful to project beyond the range of the charge (Runs 4-8). hence the entries also for Runs 9 and 10.

The proposed run plan provide a comprehensive investigation of both rare and global processes over the broadest possible range of species. The components include

- Au+Au at $\sqrt{s_{NN}}$=200 GeV, with the goal of developing the maximum possible integrated luminosity to allow measurement of charmonium, open charm, and identified particles (including direct photons) to the highest possible transverse momenta.
- Si+Si at $\sqrt{s_{NN}}$=200 GeV, to study jet quenching and charmonium production in a lighter system, together with global properties such as flow and strangeness production.

Table 3: The PHENIX Beam Use Proposal for 37 cryo weeks per year

RUN	**SPECIES**	$\sqrt{s_{NN}}$ **(GeV)**	**PHYSICS WEEKS**	$\int \mathcal{L}dt$ **(delivered)**	**p+p Equivalent**
4	Au+Au	200	19	521 μb^{-1}	20.2 pb^{-1}
	p+p	200	5	1.2 pb^{-1}	1.2 pb^{-1}
5	Si+Si	200	14	12 nb^{-1}	9.6 pb^{-1}
	p+p	200	10	10 pb^{-1}	10 pb^{-1}
6	Au+Au	62.4	19	117 μb^{-1}	4.3 pb^{-1}
	p+p	500	2	5.4 pb^{-1}	5.4 pb^{-1}
7	p+p	200	19	158 pb^{-1}	158 pb^{-1}
	p+p	62.4	5	7 pb^{-1}	7 pb^{-1}
8	Au+Au	200	29	3855μb^{-1}	150 pb^{-1}
9	p+p	500	29	966 pb^{-1}	966 pb^{-1}
10	d+Au	62.4	29	5.9 nb^{-1}	2.3 pb^{-1}

- Au+Au at $\sqrt{s_{NN}}$=62.4 GeV, with sufficient integrated luminosity to investigate the energy dependence of both global and rare phenomena.
- A re-investigation (in Run-8) of $\sqrt{s_{NN}}$=200 GeV Au+Au collisions, to take advantage of both expected enhancements in machine performance and the planned upgrades to the PHENIX detector.
- A d+Au run at $\sqrt{s_{NN}}$=62.4 GeV to perform the same calibration of high p_T particle production at that energy as was done for 200 GeV collisions in Run-3.
- A p+p run at 62.4 GeV (37 week scenario only), both to provide p+p comparison data for other systems measured at this energy and (perhaps) to perform polarized measurements in different regime of x.
- An aggressive program of development for luminosity and polarization in p+p collisions, followed by production running at both 200 and 500 GeV to measure ΔG.

Whenever possible, the various running modes in this program have been designed to provide roughly comparable parton-parton luminosities, and thus comparable sensitivities to rare processes. This may be seen by examining the "p+p equivalent" columns of Tables 2 and 3 and the physics yields columns of Tables 4 and 5.

3.2 Physics Yields

The integrated luminosities quoted in Tables 2 and 3 are calculated according the linear-ramp model provided by CAD. Given the large range between the conservative and optimistic guidance, in all cases we have chosen to use the geometric mean of these extremes as plausible yet realistic estimators of expected performance improvements. We have verified that the basic thrust of our run plan is not critically dependent on this assumption– using the optimistic guidance partially alleviates aspects of the program which are luminosity-limited (identified below), while strict adherence to the conservative guidance [2] of course only exacerbates these issues.

Table 4: Physics yields from the PHENIX run plan for 27 cryo weeks per year

RUN	SPECIES	$\sqrt{s_{NN}}$ (GeV)	PHYSICS WEEKS	$\int \mathcal{L}dt$ (recorded)	J/ψ 's N. Arm	π^0 p_T^{max} (GeV/c)	$A_{LL}(\pi^0)$ p_T^{max} (GeV/c)
4	Au+Au	200	14	123 μb^{-1}	1640	17.8	
	p+p	200	0				
5	Si+Si	200	9	2.2 nb^{-1}	1570	15.8	
	p+p	200	5	1.2 pb^{-1}	1860	15.1	6.2
6	Au+Au	62.4	19	45 μb^{-1}	120	10.4	
7	p+p	200	19	62 pb^{-1}	98,600	24.3	11.0
8	Au+Au	200	19	841μb^{-1}	11,200	22.5	
9	p+p	500	19	211pb^{-1}	944,000	39.1	19.0
10	d+Au	62.4	19	1.3nb^{-1}	102	9.0	

Physics yields from the proposed program are obtained from the delivered luminosities quoted in Tables 2 and 3 assuming a PHENIX efficiency of 60% (increased from the 50% value used in previous proposals, based on experience) and a vertex and quality assurance factor of 65% (increased from 50% used previously, based on CAD guidance). The product of the delivered luminosity and these factors will be referred to as the *recorded* luminosity, which forms the basis of all physics estimates using the calibrated methodology described in Section 2.3. The PHENIX recorded luminosity clearly places a high premium on the stated CAD goal of running the RF cavities at full voltage to obtain the design value of σ = 20 cm for the z-vertex distribution. The recorded luminosity is also useful for

[2] PHENIX also found it unrealistic to use the conservative guidance in that it would ignore not only the physical capabilities of the accelerator but also the demonstrated ability of CAD staff to make year-by-year improvements in the delivered luminosity.

Table 5: Physics yields from the PHENIX run plan for 37 cryo weeks per year

RUN	**SPECIES**	$\sqrt{s_{NN}}$ **(GeV)**	**PHYSICS WEEKS**	$\int \mathcal{L}dt$ **(recorded)**	J/ψ **'s N. Arm**	π^0 p_T^{max} **(GeV/c)**	$A_{LL}(\pi^0)$ p_T^{max} **(GeV/c)**
4	Au+Au	200	19	203 μb^{-1}	2700	19.0	
	p+p	200	5	0.5 pb^{-1}	750	13.5	5.0
5	Si+Si	200	14	4.7 nb^{-1}	3460	17.3	
	p+p	200	5	3.8 pb^{-1}	6030	17.3	7.2
6	Au+Au	62.4	19	45 μb^{-1}	120	10.4	
	p+p	500	2	2.1 pb^{-1}	9,400	22.4	9.3
7	p+p	200	22	76 pb^{-1}	122,000	24.9	11.2
		62.4	5	2.7 pb^{-1}	880	11.0	4.8
8	Au+Au	200	19	1503μb^{-1}	20,000	24.1	
9	p+p	500	29	377pb^{-1}	1,700,000	41.9	20.4
10	d+Au	62.4	29	2.3nb^{-1}	182	9.6	

comparison to previous PHENIX requests. For example, the Run-2 PHENIX Beam Use Proposal specified 300 μb^{-1} of recorded luminosity as the goal for a J/ψ measurement in Au+Au collisions at 200 GeV. Our increased understanding of J/ψ yields at RHIC[22] has demonstrated the wisdom of this value, which drives our Run-4 request. A quantitative discussion of the expected yields for this crucial channel is presented in Section 4.

4 Discussion

This section provides specific remarks for the various components of our plan. These will of course be most detailed for the Run-4 discussion, both due to its proximity and because the discussion of Run-4 physics yields is readily extensible to the latter runs by straightforward scaling of the p+p equivalent luminosities[3]. A general discussion of key points and critical observations is provided in Section 4.8.

4.1 Run-4

4.1.1 14 weeks Au+Au at $\sqrt{s_{NN}}$=200 GeV

The primary goal of this run is a definitive measurement of J/ψ production in central collisions. The ability to do this with the expected 123 μb^{-1} depends critically on the value of the suppression. Using the measured backgrounds in both the central and muon arms, and the expected yields after all cuts of e^+e- pairs (central) and $\mu^+\mu^-$ pairs (muon arm), the statistical significance of the J/ψ yield in a [0-20]% centrality bin in the case of strong suppression is (only) 2.6σ (central) and 3.2σ (muon). Here "strong suppression" is taken as factor of 5 below that of normal nuclear suppression expected from strict $A^{2\alpha}$ scaling. Since this measurement remains limited by statistical, not systematic, errors, the *significance* of the measurement improves (to a good approximation) as the square root of the integrated luminosity. Thus, modest increases in the integrated luminosity can yield major improvements in the statistical significance of the measurement. For example, a doubling of the 123 μb^{-1} has the effect of 2.6σ $\rightarrow$ 3.6σ (central) and 3.2σ $\rightarrow$ 4.5σ (muon), which of course translate into vastly improved Confidence Limits. These values demonstrate not only the wisdom of our long-stated goal of 300 μb^{-1} but also the high premium attached to developing the highest possible Au+Au integrated luminosity in this run. Failure to do so will result in a statistically ambiguous J/ψ result, and will delay the progress of the overall program of understanding the properties of heavy ion collisions at RHIC energies.

Other signals of interest remain elusive with this Run-4 request. Perhaps the best example is the ψ', where the expected yield is only of order 10-30 net counts, measured at a 1-2σ level of statistical significance (this for the case of only normal nuclear suppression). The central arms will provide a measurement of ϕ and ω decays to e^+e^- at the 3.4σ and 4.4σ level, respectively, in the [0-20]% centrality bin. Here the large backgrounds at low pair-mass preclude development of effective triggers, so that these measurements are conducted with a subset of 50 μb^{-1} of reserved bias for a minimum bias sample.

[3]In this section, all luminosities quoted will be PHENIX recorded luminosities; weeks refer to physics production weeks *after* ramp-up and set-up.

In the case of 37 weeks, we would propose extending the Au+Au portion of Run-4 by 5 weeks, to increase the integrated luminosity to 203 μb^{-1}, thereby obtaining a corresponding additional reach in statistical sensitivity, as per the scaling behavior noted above.

4.1.2 p+p Development Run

We request that 5 weeks of Run-4 be used for a dedicated period of machine development, as per the statement from CAD quoted in Section 2.2.3. That this request is made in spite of the serious concerns expressed in the previous section regarding integrated luminosity in Au+Au running is an indication of how critical the timely development of adequate polarization and luminosity is to the goals of the spin program. (It also demonstrates the inherent inefficiencies of running only 27 weeks per year, and implicitly argues that even modest increases in the yearly running could lead to substantial gains in overall progress.) This period is expected to consist of the standard 2 week set-up period followed by 3 weeks of studies, and does not have physics running in Run-4 as an end goal.

While the specifics of the requested machine development will be determined by CAD, we note that they are likely to include reducing the variation of betatron tune during acceleration, increasing understanding of the tune-shift limitations on luminosity, commissioning of the hydrogen jet target at IP12, tune feedback and spin flipper commissioning, and studies of improved polarization in RHIC due to the repaired Yellow ring snake and the increases at AGS extraction due to the helical dipole partial Siberian Snake (to be commissioned parasitically during Au+Au running).

In the case of 37 weeks, we would propose passing from machine development to a 5 week period of polarized running. If in fact a significant increase in polarization is provided by the development work, then a relatively short run could offer significant gains in sensitivity. In Table 5 we have assumed an average polarization of 40%, which implies that the 0.5 pb^{-1} listed there represents factor of 7 improvement in $\mathcal{P}^4 \int \mathcal{L}dt$ over the Run-3 data set. Given that such a period of spin physics running would contribute significantly to the overall vitality of this important physics program, we ask that every effort be made to find additional weeks in Run-4 beyond the nominal 27.

4.2 Run-5

4.2.1 9 weeks Si+Si at $\sqrt{s_{NN}}$=200 GeV

The focus in this run is the study of nuclear collisions at the same energy but in a significantly smaller system. We have selected Si for this purpose, noting that it is intermediate in $A^{1/3}$ between p+p and Au+Au collisions, and that the choice of this control parameter is appropriate for both parton energy loss (Length $\sim A^{1/3}$) and saturation physics ($Q_s^2 \sim A^{1/3}$). There is also extensive experience with the acceleration of Si ions in both the Tandem and the AGS, which is important for developing the maximum luminosity in RHIC for this species as rapidly as possible. Our implementation of the CAD guidance predicts a PHENIX recorded luminosity of 2.2 nb^{-1}, equivalent to a p+p sample of 1.7 pb^{-1}. The parton-parton flux is thus roughly comparable to the planned high-luminosity Au+Au run, leading to a quality comparison measurement of high-p_T particle and J/ψ production in this much lighter system, as well as the corresponding global features such as flow and strangeness production.

In the 37 week scenario, this run is extended by 5 weeks, more than doubling the integrated luminosity.

4.2.2 5 weeks p+p at 200 GeV

Following the proton development work in Run-4, this is anticipated as the first spin physics production run. We have assumed that the average polarization will be of order 50%. Combined with the CAD-predicted luminosity growth, this provides a PHENIX recorded luminosity of 1.2 pb^{-1} leading to a factor of 40 improvement in $\mathcal{P}^4 \int \mathcal{L}dt$ over the Run-3 data set. The polarized gas jet target should be available for this run, and will provide an absolute measurement of the beam polarization at 100 GeV (per beam).

In the case of 37 weeks, 5 of the additional weeks would be allocated to polarized proton running, more than tripling the integrated luminosity compared to that of the 27 week scenario.

4.3 Run-6

4.3.1 19 weeks of Au+Au at $\sqrt{s_{NN}}$=62.4 GeV

The goal of this run is to provide a *definitive* test measurement of the energy dependence of suppression effects in Au+Au collisions. To do so with p_T range comparable to even the existing Run-3 measurements is extremely challenging, in that production cross sections fall rapidly with $\sqrt{s}$, as does the RHIC luminosity (as the square of the beam energy). The combination of these two reductions require a dedicated run in order to perform a viable measurement. The energy is chosen to duplicate that of previous p+p measurements from the CERN ISR, a particularly important consideration in the strict 27 week scenario, in which we can not accommodate a corresponding p+p comparison run within the (extended) scope of this 5-year plan.

4.3.2 2 weeks of p+p at 500 GeV (37 weeks only)

In the case of 37 cryo weeks, we advocate a first investigation of polarized protons at 500 GeV. The modest integrated luminosity (2.1pb^{-1}) results from the additional 3 weeks (in addition to the canonical 2 set-up + 3 ramp-up) specified in the CAD guidance for commissioning at 500 GeV[4]. Even if this entire additional period is required, it is still possible to accelerate the spin program very substantially with this first look at 500 GeV provided by the remaining 2 weeks of physics running. This is an instructive example of the tremendous incremental benefit of increased running time.

4.4 Run-7

Our plan calls for dedicated production running for spin, i.e., the full period of 19 weeks used for p+p collisions at 200 GeV. This produces sufficient integrated luminosity (62 pb^{-1} to provide a superb measure of A_{LL} via π^0's and rough results on the same quantity via direct photons.) In the case of 37 weeks, this would remain a dedicated spin run, but would offer the possibility of beginning with a short run (listed here as 5 weeks) at 62.4 GeV, to provide *in situ* measurement of comparison data for the Au+Au Run-6 measurement at this energy. This possibility is not present in the 27 week scenario, and is an example of an important measure that is possible in 37 weeks but not in 27 weeks per year. Note that for this energy change (only) we have used the 2 week estimate from CAD for the change-over, as opposed to the 5 week value used when changing species. The precise duration of each segment is of course flexible; here we have used the 5 weeks (62.4 GeV) and 22 weeks (200 GeV) as an example.

4.5 Run-8

In both the 27 and 37 week version of our plan, we envisage a return to full energy Au+Au running, with the goal of exploiting the anticipated luminosity improvements in RHIC to substantially increase sensitivity in rare channels (recall the discussion of elusive measurements in Section 4.1.1). Factors of 6 to 7 improvements over the Run-4 data set appear possible. Moreover, the upgrades[66] planned for Run-8 will provide PHENIX with very substantial additional capabilities for charm measurements (via a Si-vertex counter) and low-mass dileptons (via a Hadron Blind Detector), greatly extending our understanding of in-medium effects in Au+Au collisions at RHIC.

[4]Of particular concern are the additional spin resonances that must be crossed in accelerating each beam from 100 to 250 GeV.

4.6 Run-9

Continuing the pattern of dedicated runs to pursue rare physics, our plan calls for extended spin running at 500 GeV. The large integrated luminosity developed during this dedicated run, together with the high center-of-mass energy, will permit measurement of sea quark polarization via $W^{\pm}$ production. (A proposal for an improved muon trigger for W's is currently under preparation for submission to NSF.)

4.7 Run-10

It should be clear that the resolution of any beam use plan for six years in the future is extremely coarse. For illustrative purposes only, we have considered the feasibility of a d+Au run at the lower 62.4 GeV measured in Run-6 in Au+Au collisions. Once more, the low energy requires the use of the entire 27 or 37 week period to make an effective measurement with p_T reach comparable to the other data sets. We note that with this run, the ion program will have measured (in the 37 week scenario) two (62.4 GeV and 200 GeV) complete (Au+Au, d+Au, p+p) data sets, together with a 200 GeV Si+Si measurement. Even with 37 weeks, there are measurements (e.g., d+Si at either energy, Fe+Fe) yet to be explored. We choose to view this as a statement of promise for many additional runs beyond the scope of this proposal.

4.8 Discussion Summary

It is appropriate to augment the specific discussion of the previous section with some general observations derived from this multi-year planning process. We provide some of these below in itemized form:

- *The first, most obvious and most urgent point is that a steady-state situation of only 27 weeks of cryogenic operations will have a large and negative impact on the overall physics productivity of RHIC.* A partial indication of this is shown in Figure 12, which shows that the 27 weeks develops nearly a factor of two less integrated luminosity than a 37 weeks per year scenario. This figure actually under-emphasizes the adverse impact, as entire measurements present in 37 weeks (e.g., Run-6 500 GeV running, Run-7 62.4 GeV p+p running) can not be performed in the 27 week program. While world-class physics is produced by the 27 week scenario, the most efficient realization of the true potential of RHIC results for running periods of 32-37 weeks per year. To minimize the deleterious impact of years with only 27 weeks of operations, the effort to secure additional running weeks must begin immediately and must extend throughout the life of the program.

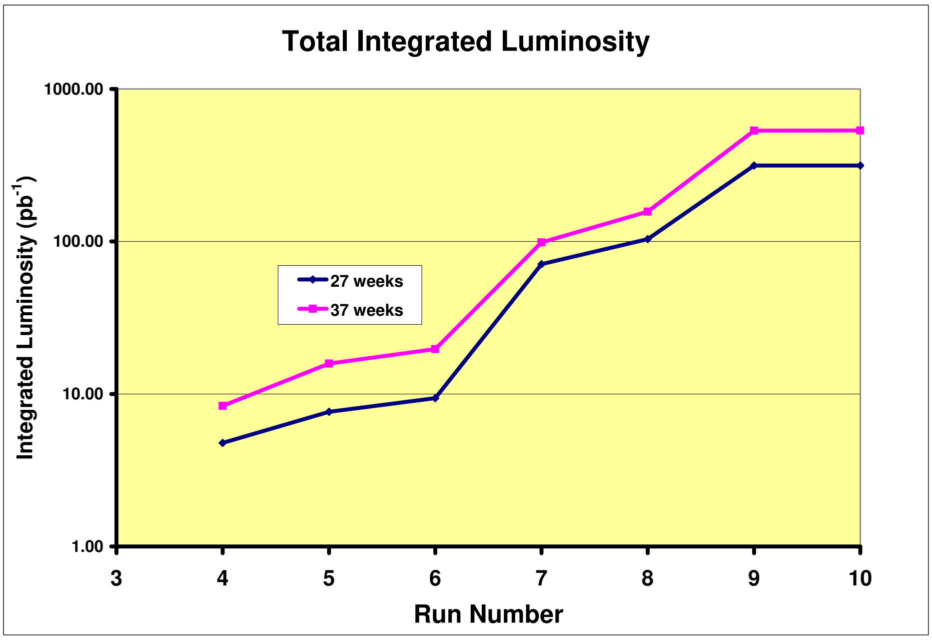

Figure 12: A comparison of the total parton-parton integrated luminosity, normalized to the proton+proton equivalent, versus run number for the 27 and 37 week scenarios. The programmatic differences are in fact larger than would be suggested from this simple comparison, in that 37 weeks permits additional modes not found in the program with only 27 weeks per year of operations.

- To maximize the discovery potential so evident in the first three years of RHIC operations, it is advantageous to pursue each running mode to the limit of available luminosity, and to balance the integrated luminosities between modes to develop equivalent parton-parton flux (and thus p_T reach) in all comparison data sets.

- A multi-year plan often does not survive its first encounter with reality. We have not provided a detailed discussion of branch points, in that they greatly expand the phase space of available options. Nonetheless, two are worth mention as examples of future decisions that may be required. The first would result from failure to make a definitive measurement of J/ψ production in Run-4. Should this be due to solvable issues with available luminosity, we would modify our request to call for a second Au+Au run at the earliest possible time in the future runs. A different branch point could result from observation of J/ψ enhancements in Run-4. If so, this could lead to a request for the long low energy run planned for Run-6 to be moved to Run-5 (*provided* that the nature of the enhancement was sufficient to overcome the much lower J/ψ production cross section at 62.4 GeV). Another source of such decision points would be early availability of various proposed upgrades, which (for example) could access new channels in a previously measured species.

- In our plan, we have applied a strategy of single-species runs for RHIC Run-6 and beyond. This is clearly the most efficient usage of cryogenic weeks. Mitigating this in the first five years of operation are the needs of both the ion and the spin program to understand and overcome various machine limitations in luminosity and polarization. Full utilization of the accelerator will result when these long development periods are no longer necessary, and/or when rapid mode-switching permits multi-species runs without the 5 week overheads and the multi-week luminosity ramps.

- For planning purposes, we have applied a strict form of the 27 and 37 week scenarios, and have not investigated in detail efficiencies which could result from splitting funding across fiscal year boundaries. Again, this greatly expands the phase space of available solutions, so we simply note that there are possible advantages to alternating 36 and 18 week running modes that should be explored.

We conclude with a brief statement regarding upgrades. This is already an ongoing process in PHENIX, as is apparent from the discussion in Section 1.1 of added capabilities to be provided by the aerogel detectors added for Run-4. There is also an active R&D program[66] developing detailed proposals for Si-vertex detectors, a Hadron Blind Detector, an inner TPC, and a greatly enhanced muon trigger. The availability of these significant additions to PHENIX depend on the R&D efforts, the proposal process, and the subsequent funding. We have attempted to incorporate the planned delivery of these items into our planning process, but also realize that the detailed time sequence is subject to many as yet unknown constraints. The run plan developed here is possible without these additional systems[5], but made even more compelling should any or all of them become available over the scope of this plan.

[5]The muon trigger is an exception to this statement; it will be essential for efficient triggering in high luminosity p+p running at 500 GeV.

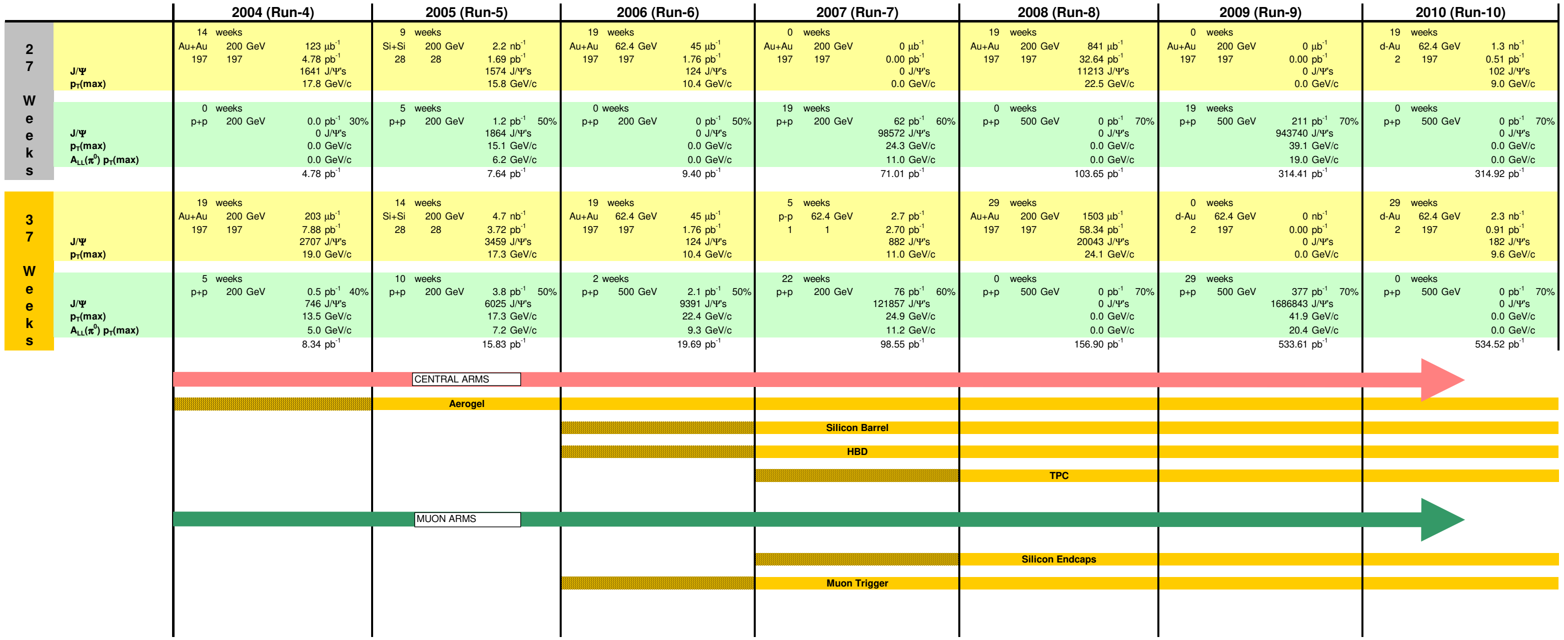

Figure 13: A snapshot of the run planning spreadsheet, showing recorded luminosities and physics versus year.

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