Relevance of baseline hard proton-proton spectra for high-energy nucleus-nucleus physics

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Abstract. We discuss three different cases of hard inclusive spectra in proton-proton collisions: high $p_T$ single hadron production at $\sqrt{s} \approx 20$ GeV and at $\sqrt{s} = 62.4$ GeV, and direct photon production at $\sqrt{s} = 200$ GeV; with regard to their relevance for the search of Quark Gluon Plasma signals in A+A collisions at SPS and RHIC energies.

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Introduction

The study of the fundamental theory of the strong interaction, Quantum Chromo Dynamics (QCD), in extreme conditions of densities and temperatures has attracted much experimental and theoretical interest in recent years. Experimentally, the only available means to investigate the many-body chromo-dynamics of a dense and hot system of partons involves the use of large atomic nuclei collided at relativistic energies. In this context, the primary goal of high-energy nucleus-nucleus collisions is the creation and study in the laboratory of a deconfined state of “plasma of quarks and gluons” (QGP) predicted by QCD calculations on the lattice \[ \Box \] for values of the energy density, $\epsilon \gtrsim 0.7$ GeV/fm$^3$, five times larger than those found in the nuclear ground state.

The search of QGP signals in the A+A data relies strongly on direct comparison to reference results from proton-proton collisions in free space as they provide the “QCD vacuum” baseline to which one compares the heavy-ion results in order to extract information about the properties of the produced hot and dense QCD medium. Among all available experimental observables, hard probes provide the most direct information on the fundamental quark and gluon degrees of freedom. Indeed, in all hadronic collisions (p+p, p+A or A+A), the production of particles with high transverse momentum (jets, single hadrons with $p_T \gtrsim 2$ GeV/c, prompt $\gamma$) or large mass (heavy quarks), results from
direct parton-parton scatterings with large momentum transfer $Q^2$ ("hard processes"). Since the hard cross-sections can be theoretically calculable by perturbative methods via the collinear factorization theorem \[^2\], inclusive high $p_T$ hadrons, jets, direct photons, Drell-Yan, and heavy flavors, have long been considered both experimentally and theoretically sensitive and well calibrated probes of the small-distance QCD phenomena.

Simple arguments based on QCD factorization for hard cross-sections in A+A collisions (with its implicit premise of incoherent parton-parton scattering) \[^3\], and direct experimental measurements of Drell-Yan production in Pb+Pb at CERN-SPS \[^4\], and of prompt-$\gamma$ \[^5\] and total charm yields \[^6\] in Au+Au at BNL-RHIC, support that hard inclusive cross-sections in A+A reactions scale simply as $A^2$ times the corresponding hard p+p cross-sections: $E d\sigma_{\text{hard}}^{A+A \rightarrow hX}/d^3p = A^2 \cdot E d\sigma_{\text{hard}}^{p+p \rightarrow hX}/d^3p$. For a given centrality bin (or impact parameter $b$) in a nucleus-nucleus reaction, such a simple scaling rule translates into the so-called "$N_{\text{coll}}$ (binary) scaling" relation between hard p+p cross-sections and A+A yields: $E dN_{\text{A}A \rightarrow hX}/d^3p(b) = \langle T_{AA}(b) \rangle \cdot E d\sigma_{\text{pp} \rightarrow hX}/d^3p$, where $T_{AA}(b)$ is the Glauber (eikonal) nuclear overlap function \[^\parallel\] at $b$. The standard method to quantify the effects of the medium in a given hard probe produced in a A+A reaction is, thus, given by the nuclear modification factor:

$$R_{AA}(p_T, y; b) = \frac{\text{"hot/dense QCD medium"}}{\text{"QCD vacuum"}} = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b) \rangle \times d^2\sigma_{pp}/dydp_T},$$

which measures the deviation of A+A at $b$ from an incoherent superposition of NN collisions.

In this paper we discuss experimental results on inclusive single hadrons at high $p_T$ in p+p and A+A collisions at top CERN-SPS energies ($\sqrt{s} \approx 20$ GeV) and intermediate RHIC energies ($\sqrt{s} = 62.4$ GeV), as well as theoretical expectations on direct photon production in p+p and A+A collisions at top RHIC energies ($\sqrt{s} = 200$ GeV). The corresponding high $p_T$ hadron and photon A+A nuclear modification factors provide, respectively, critical information on established QGP signals such as high $p_T$ leading hadron suppression (due to parton energy loss in the deconfined system) and thermal photon emission from the plasma.

**Case I: High $p_T$ p+p $\rightarrow \pi^0 + X$ reference at $\sqrt{s} \approx 20$ GeV**

One of the canonical signatures of QGP formation in A+A collisions is the observation of a suppressed production of high $p_T$ leading hadrons (as compared to p+p collisions in free space) due to the non-Abelian energy loss of the parent parton traversing the dense medium produced in the A+A reaction ("jet quenching") \[^7\]. In agreement with these expectations, high-$p_T$ hadroproduction in central Au+Au collisions at $\sqrt{s_{NN}} = 130$, 200 GeV at RHIC has been found to be strongly suppressed (by up to a factor of 4–5)

\[^\parallel\] The term "$N_{\text{coll}}$ scaling" comes from the fact that the average number of nucleon-nucleon (NN) collisions at $b$ is simply $\langle N_{\text{coll}}(b) \rangle = \langle T_{AA}(b) \rangle \cdot \sigma_{pp}^{\text{inel}}$. 

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Compared to p+p collisions measured at the same $\sqrt{s_{NN}}$ [14, 11], high $p_T$ pion production in central A+A at CERN-SPS energies was found not to be suppressed but enhanced compared to production in free space [13, 16, 17]. Such a “Cronin effect” was consistent with previous observations in fixed-target p+A collisions at Fermilab ($\sqrt{s_{NN}} \approx 20 - 40$ GeV) [18, 19, 20] and in $\alpha + \alpha$ interactions at the ISR collider ($\sqrt{s_{NN}} = 31$ GeV) [21]. The prevalence of the Cronin broadening, characteristic “cold QCD matter” systems, in A+A reactions at the SPS suggested that multiple initial-state (soft) $k_T$ “kicks” suffered by the colliding parton in their way through the nucleus dominated over possible final-state energy-loss effects for center-of-mass energies of order $\sqrt{s_{NN}} \approx 20$ GeV.

A recent reanalysis of the SPS results [22] has shown, however, that the apparent strong pion enhancement observed is not actually supported by the A+A data but is due to the use of inexact p+p baseline references. Indeed, since no concurrent measurement of high $p_T$ pion production in proton-proton collisions was carried out at SPS at the same $\sqrt{s}$ as the heavy-ion experiments (and given that perturbative QCD calculations are not reliable in this relatively low energy domain) one had to count on p+p parametrizations extrapolated from data at higher collision energies. On the one hand, the WA98 collaboration [15] employed a empirical power-law form $A \left[ p_0 / (p_T + p_0) \right]^n$ (originally proposed by Hagedorn [23]) tuned to reproduce the ISR p+p pion spectra ($\sqrt{s} \approx 20 - 31$ GeV), plus an $x_T$ scaling prescription [24] to account for the collision energy dependence of the cross section. On the other hand, Wang&Wang [17] adopted a more complex power-law ansatz for the $p_T$ spectrum which described the charged pion data at $\sqrt{s} = 19.4$ GeV [19], combined with a pQCD parton model calculation to scale the cross-section down to $\sqrt{s} = 17.3$ GeV. Though both parametrizations were tuned to reproduce a subset of the existing p+p $\rightarrow \pi^+X$ data at $\sqrt{s} \approx 20$ GeV, no true global analysis was carried out to fully compare the parametrizations to all the existing data in this energy regime.

Figure 1 (left) shows all single inclusive pion spectra measured at high $p_T$ in p+p,¯ p collisions in the same $\sqrt{s}$ range of the CERN-SPS heavy-ion experiments, whereas the plot in Figure 1 (right) shows the relevant parton kinematical domain for hard hadro-production in this energy regime. Fig. 2 confronts the two proposed parametrizations to the experimental data. Both parametrizations fail to describe adequately the shape of the $p_T$ spectra, and both undershoot the cross-sections by as much as by factors of 2–3 of the same order as the reported Cronin enhancements.

As an alternative to the WA98 and Wang&Wang p+p references, we proposed [22] to employ a purely empirical 11-parameter functional form derived by Blattning et al [29] from a global analysis of most of the available proton-proton $\pi^0$ spectra measured in the range $\sqrt{s} \approx 7 – 63$ GeV. Fig. 3 shows that the level of agreement of the Blattning

Note that, as discussed in [22], the $\pi^0$ data of [25] plotted in Figs. 1, 2 have been even scaled down by a factor of 0.8 above $p_T = 1.5$ GeV/c to take into account the $\eta$ contamination not subtracted in the original tabulated results (see a discussion of this effect in Section 11.2.3).
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Figure 1. Left: Compilation of single inclusive pion spectra measured at high \( p_T \) (\( p_T \gtrsim 2 \text{ GeV/c} \)) in p+p collisions \[11, 20, 23, 27\] in the same collision energy range (\( \sqrt{s} = 16.9 - 19.4 \text{ GeV} \)) as the CERN-SPS A+A experiments. Right: Scaling variables \( \langle x_1, x_2 \rangle \) (average parton fractional momentum) and \( \langle z \rangle \) (average momentum fraction of the parent parton carried by the leading pion) for p+p \( \rightarrow \pi^0 \) production (\( \sqrt{s} = 17.3 \text{ GeV} \)) at mid-rapidity versus the \( \pi^0 \) momentum, computed in perturbative QCD \[28\].

parametrization to the p+p pion cross-sections of Fig. 2 is more satisfactory, both in shape and magnitude, than the two previous parametrizations at least within the \( p_T \) range (\( p_T \approx 1.5 - 3.5 \text{ GeV/c} \)) covered by the heavy-ion experiments. Importantly, the p+p parametrization describes reasonable well the \( \sqrt{s} \) dependence of the yields which is a critical requirement for using it as a fair baseline for the Pb+Pb and Pb+Au data at \( \sqrt{s_{NN}} = 17.3 \text{ GeV} \).

Using the reference of Blattnig et. al, we revised in \[22\] the nuclear modifications factors for the whole set of high \( p_T \) data from the SPS heavy-ion programme: \( \pi^0 \) and \( \pi^\pm \) at \( \sqrt{s_{NN}} = 17.3 \text{ GeV} \) from Pb+Pb (WA98) \[15\] and Pb+Au (CERES/NA45) \[30\] respectively, and \( \pi^0 \) from S+Au at \( \sqrt{s_{NN}} = 19.4 \text{ GeV} \) (WA80) \[31\]. The revisited \( R_{AA} \), plotted in Figure 4 indicate that high-\( p_T \) hadroproduction at \( \sqrt{s_{NN}} \approx 20 \text{ GeV} \) is not enhanced in central nucleus-nucleus reactions but, within errors, is consistent instead with scaling with the number of \( NN \) collisions. Interestingly, at variance with central collisions, high \( p_T \) pion production in peripheral Pb+Pb reactions at SPS is indeed enhanced by as much as by a factor of \( \sim 2 \) compared to the “\( N_{cold} \) scaling” expectation \[15, 22\]. This fact indicates that there must exist a mechanism in central A+A that “neutralizes” the Cronin enhancement down to values consistent with \( R_{AA} \approx 1 \). Theoretical predictions \[32\] of high \( p_T \) \( \pi^0 \) production in central Pb+Pb collisions including Cronin broadening and (anti)shadowing supplemented with final-state partonic energy loss in an expanding dense system with effective gluon densities
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$dN^0/dy = 400–600$ reproduce well the observed suppression factor (yellow band in Fig. 5) supporting the idea that a moderate amount of jet quenching is already present in the most central heavy-ion reactions at SPS. The confirmation of this conclusion requires, however, a direct (and accurate) measurement of the high $p_T$ $p+p$ pion cross-section at $\sqrt{s} = 17.3$ GeV. Unfortunately, although RHIC can run Au+Au at a similar center-of-mass energy of $\sqrt{s_{NN}} = 19.6$ GeV (corresponding to the 9 GeV injection energy from AGS), the minimum collision energy in the proton-proton mode is $\sqrt{s} = 48.6$ GeV (the RHIC design injection energy for each proton beam from AGS is 24 GeV, above the transition energy of 22 GeV) \[33\]. This fact hinders the possibility of directly comparing high $p_T$ hadroproduction in $A+A$ and $p+p$ collisions at RHIC at center-of-mass energies comparable to SPS.

Figure 2. Relative differences between the single inclusive pion spectra measured in $p+p$ collisions at $\sqrt{s} = 16.9 - 19.4$ GeV \[19, 25, 26, 27\] and the $p+p \rightarrow \pi^0+X$ parametrizations proposed by the WA98 collaboration \[15\] (upper figure) and Wang&Wang \[17\] (lower figure) at the corresponding $\sqrt{s}$. The shaded band represents the 20% overall uncertainty assigned originally to the WA98 parametrization. Wang&Wang only provides the fit parameters for 2 fixed values of $\sqrt{s} = 17.3, 19.4$ GeV.
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Figure 3. Relative differences between the single inclusive pion spectra measured in p+p collisions at $\sqrt{s} = 16.9 - 19.4$ GeV [19, 25, 26, 27] and the p+p $\rightarrow \pi^0+X$ parametrization derived in ref. [29]. The shaded band represents the 25% overall uncertainty that we assign to the parametrization.

Figure 4. Nuclear modification factors for pion production at CERN-SPS in central Pb+Pb [15], Pb+Au [30], and S+Au [31] reactions at $\sqrt{s_{NN}} \approx 20$ GeV, and at ISR in minimum bias $\alpha+\alpha$ reactions at $\sqrt{s_{NN}} = 31$ GeV [21]. The $R_{AA}$ from SPS are obtained using the p+p parametrization proposed in ref. [22]. The $R_{AA}$ for ISR $\alpha+\alpha$ has been obtained using the p+p spectrum measured in the same experiment [21]. The shaded band at $R_{AA} = 1$ represents the overall fractional uncertainty (including in quadrature the 25% uncertainty of the p+p reference and the 10% error of the Glauber calculation of $N_{coll}$). CERES data [30] have an additional overall uncertainty of $\pm 15\%$ not shown in the plot.
Case II: High $p_T$ $p+p \to \pi^0, h^\pm + X$ references at $\sqrt{s} = 62.4$ GeV.

The study of the excitation function of high $p_T$ hadron suppression between top SPS and top RHIC energies was the main motivation behind the dedicated Au+Au run at RHIC intermediate energies ($\sqrt{s_{NN}} = 62.4$ GeV) carried out in April 2004. PHENIX measured charged hadrons up to $p_T = 5$ GeV/$c$ and identified neutral pions in the range $p_T = 1 - 7$ GeV/$c$ \[34\]. PHOBOS \[35\] and STAR \[36\] measured inclusive charged hadrons up to $p_T \approx 4.5$ GeV/$c$ and 12 GeV/$c$ respectively. However, as in the SPS case, no concurrent $p+p$ reference measurement was performed at $\sqrt{s} = 62.4$ GeV, and the corresponding Au+Au nuclear modifications factors were constructed using, basically, $p+p \to h^\pm, \pi^0$ differential cross-sections measured in the 70s and 80s at the top ISR energies ($\sqrt{s} = 62 - 63$ GeV). Table II collects all the existing measurements of high $p_T$ (neutral and charged) pion and inclusive charged hadrons in proton-proton collisions at the maximum CERN-ISR energy.

II.1. $p+p \to h^\pm + X$ reference at $\sqrt{s} = 62.4$ GeV

Rather than using the existing ISR $h^\pm$ data at $\sqrt{s} = 62 - 63$ GeV, the PHENIX $p+p$ inclusive charged hadron reference at $\sqrt{s} = 62.4$ GeV has been independently obtained \[52\] by interpolating from lower and higher collision energy measurements$^+$: $p+p$ at $\sqrt{s} = 130$ GeV \[8\].

$^+$ The same procedure was followed to obtain the $p+p$ reference for RHIC Run-1 Au+Au measurement at $\sqrt{s} = 130$ GeV \[8\].
| Reaction | $\sqrt{s}$ (GeV) | Collab./Exp. | Ref. | $y$ | $p_T$ range (GeV/c) | Data points | Energy scale error in yield (%) | Extra syst. & abs.norm. error correction | $\sqrt{s}$ correction | direct-$\gamma$ correction | $\eta$ correction |
|-----------|------------------|--------------|------|-----|---------------------|-------------|----------------------------------|------------------------------------------|-------------------|-----------------|----------------|
| $p+p \rightarrow \pi^0 + X$ | 62.4 | CCR (busser73) | 57, 58 | 0.0 | 2.9 – 4.6 | 7 | 55% (6%) | – | not needed | needed | needed |
| $p+p \rightarrow \pi^0 + X$ | 62.9 | ACHM (eggert75) | 59 | 0.0 | 0.7 – 6.4 | 29 | 35% (5%) | 5% | needed | needed | needed |
| $p+p \rightarrow \pi^0 + X$ | 62.4 | CCRS (busser76) | 60 | 0.0 | 2.4 – 6.2 | 40 | 26% (3%) | – | not needed | needed | not needed |
| $p+p \rightarrow \pi^0 + X$ | 63 | CSZ (clark78) | 61 | 0.0 | 5.2 – 16.5 | 17 | 25% (3%±2%) | 17% | needed | needed | needed |
| $p+p \rightarrow \pi^0 + X$ | 62.4 | CCORS/108 (busser76) | 62 | 0.0 | 3.7 – 13.7 | 21 | 25% (5%) | 5% | not needed | needed | needed |
| $p+p \rightarrow \pi^0 + X$ | 62.4 | R-806 (kourkou80) | 63 | 0.0 | 3.0 – 15.0 | 28 | 22% | – | not needed | needed | not needed |
| $p+p \rightarrow m^0 + X$ | 62.8 | R-806 (kourkou80) | 64 | 0.0 | 3.0 – 15.0 | 41 | 35% (*) | – | needed | not needed | not needed |
| $p+p \rightarrow \pi^0 + X$ | 62.4 | AFS (akesson89) | 65 | 0.0 | 4.7 – 9.0 | 7 | 25% (5%) | 17% | not needed | not needed | needed |
| $p+p \rightarrow \pi^0 + X$ | 63 | AFS (acessor89) | 66 | 0.0 | 4.7 – 13.7 | 11 | – (**) | – | needed | not needed | not needed |
| $p+p \rightarrow \pi^0 + X$ | 63 | Brit.-Scand. | (alper75) | 67 | 0.0 | 0.1 – 2.4 | 17 | – | – | not needed† | – | – |
| $p+p \rightarrow \pi^0 + X$ | 62 | CCORS (busser76) | 68 | 0.0 | 3.3 – 8.0 | 22 | – | – | not needed | – | – |
| $p+p \rightarrow \pi^0 + X$ | 62 | Saclay (banner77) | 69 | 0.0 | 0.2 – 1.5 | 21 | – | – | not needed | – | – |
| $p+p \rightarrow \pi^0 + X$ | 63 | SFM (drijard82) | 70 | 0.8 | 3.8 – 12.5 | 21 | – | – | needed | – | – |
| $p+p \rightarrow \pi^0 + X$ | 63 | AFS (akesson82) | 71 | 0.0 | 2.25 – 5.8 | 10 | – | – | not needed† | – | – |
| $p+p \rightarrow \pi^0 + X$ | 63 | CDHW (breakst95) | 72 | 0.25 | 0.25 – 3.0 | 11 | – | – | not needed† | – | – |
| $p+p \rightarrow \pi^0 + X$ | 63 | CDHW (breakst95) | 73 | 0.75 | 0.25 – 3.0 | 11 | – | – | not needed† | – | – |

Table 1. Chronological compilation of $\pi^0 \pm [\not m^0 = \pi^0 + \eta]$, and inclusive charged ($h^\pm$) production measured at the top CERN-ISR energies. For each (1) reaction, we quote the (2) center-of-mass energy, (3) collaboration/experiment name, (4) bibliographical reference, (5) rapidity domain, (6) measured $p_T$ range (center of min. and max. bins quoted), (7) total number of data points, (8) $\pi^0$ energy-scale errors (the value in parenthesis is the true energy-scale uncertainty and the uncertainty quoted is the total effect of the error propagated to the yields), (9) additional systematic and/or absolute normalization (luminosity) errors [(*)] Kourkoumelis et al. energy scale error includes all syst. uncertainties and is an average over $p_T$ (error values quoted in the paper are in the range 27%–42%). (***) Akesson et al. original point-to-point errors include all uncertainties]. Column (10) lists those measurements that have been corrected to account for the (slightly) different ISR ($\sqrt{s} = 62. – 63.$ GeV) and RHIC ($\sqrt{s} = 62.4$ GeV) center-of-mass energies (those data sets marked with a dagger ($†$) have not been revised since they cover low $p_T$ values where the effect of the correction on the yields is minimal). Columns (11) and (12) indicate whether the published $\pi^0$ spectrum has been corrected for direct-$\gamma$ and $\eta$ “contaminations” resp. as described in the text.
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21, 31, 44, and 53 GeV at CERN-ISR 47, PHENIX p+p at 200 GeV, and CERN-UA1 p+\bar{p} data at 200, 500, and 900 GeV 57. Fig. 6 shows an example of the cross-section interpolation procedure in four individual p_T bins from the lower and higher \( \sqrt{s} \) measurements. The resulting interpolated spectrum at 62.4 GeV is fitted to a modified power-law form: 

\[
E d^3 \sigma_{pp\rightarrow hX}/d^3p = A \left( e^{ax + p_T/p_0} \right)^{-n},
\]

with preliminary parameters \( A = 196.4 \text{ [mb GeV}^{-2} c^3], a = 0.0226 \text{ [GeV}^{-1} c], p_0 = 2.301 \text{ [GeV/c]}, \) and \( n = 14.86; \) with an assigned overall uncertainty of ±25% 52. As an independent cross-check the fit is compared (Fig. 7) to the three ISR h± data sets measured at 63 GeV (three bottom rows of Table 1). The agreement data–fit is good within the assigned ±25% uncertainty of the parametrization.

PHOBOS 35 fitted the experimental p+p data from the CDHW experiment 51 at \( \eta = 0.75 \) (the same rapidity range of their spectrometer) to the following expression:

\[
E d^3 \sigma_{pp\rightarrow hX}/d^3p = A \left( 1 + p_T/p_0 \right)^{-n} p_T/\sqrt{p_T^2 + a},
\]

with \( A = 244.5 \text{ [mb GeV}^{-2} c^3], p_0 = 2.188 \text{ [GeV/c]}, a = 0.0085 \text{ [GeV}^2/c^2], \) and \( n = 15.37. \) STAR preliminary reference p+p spectrum 36 used a Hagedorn power-law form, \( A \left[ 1 + p_T/p_0 \right]^{-n}, \) with parameters \( A = 292.48 \text{ [mb GeV}^{-2} c^3], p_0 = 1.75 \text{ [GeV/c]}, \) and \( n = 13.23. \) Fig. 6 compares the 3 parametrizations to the existing ISR inclusive charged hadron cross-sections at 63 GeV. The 3 parametrizations agree among each other (and the data) within ±20%. A direct measurement of the inclusive charged hadron production at large p_T in p+p collisions in a dedicated run at \( \sqrt{s} = 62.4 \) GeV at RHIC is mandatory, however, if one wants to...
reduce the corresponding uncertainties propagated to the Au+Au nuclear modification factors and constrain more quantitatively the model predictions for the parton energy loss excitation function (see Section II.3).

Figure 7. Upper: Inclusive charged hadron spectra measured in p+p collisions at $\sqrt{s} = 63$ GeV at CERN-ISR [50, 51] at midrapidity ($\eta = 0, 0.25$) and moderately forward rapidities ($\eta = 0.75$) compared to PHENIX [52], PHOBOS [35] and STAR [36] $h^\pm$ parametrizations. Lower: Ratios of the same experimental spectra over the three parametrizations (each one evaluated in their valid range of rapidities).
II.2. $p+p \rightarrow \pi^0 + X$ reference at $\sqrt{s} = 62.4$ GeV

In order to obtain a benchmark $p+p \rightarrow \pi^0 + X$ reference spectrum at $\sqrt{s} = 62.4$ GeV we first collected (Table 1) all existing experimental $\pi^0$ (9 measurements [37–38, 39, 40–41, 42, 43–44, 45, 46]), $\pi^\pm$ (4 measurements [40, 47–48, 49]) and $h^\pm$ (3 measurements [50, 51]) at the highest ISR collider energies ($\sqrt{s} = 62 – 63$ GeV) and added in quadrature the original systematic and normalization uncertainties to the point-to-point errors. We included in our compilation the averaged $(\pi^+ + \pi^-)/2$ spectra* as well as the inclusive charged hadron spectra divided by the measured $h^\pm/\pi = 1.6 \pm 0.16$ ratio (Fig. 8) since this provided us with additional constraints for our global fit analysis at relatively low $p_T$ where no neutral pion data is available. The corresponding data points (adding to a total of $\sim$300) were fitted to a common functional form. The ratio of the weighted average fit over each data set is shown in the upper plot of Fig. 9. Large differences in the shape of the $p_T$ distributions and in the magnitude of the cross-sections are evident which implies that many of the measurements are inconsistent among each other well beyond the originally quoted uncertainties.

Investigation of the original published results indicates, however, several relevant differences affecting the experimental measurements. First, although at first sight discrepancies of order $\sim$1 GeV in the center-of-mass energy should not dramatically modify the single $\pi^0$ spectra, it turns out that at very high $p_T$ the absolute difference in the perturbative yields between $\sqrt{s} = 62$ GeV and 63 GeV can indeed be as large as $\sim$20% (Fig. 10). Secondly and most important, only one experiment (Akesson et al. [46]) fully identified neutral pions via a standard invariant mass analysis of photon pairs. The rest of the experiments either did not separate the $\gamma\gamma$ decay of $\pi^0$ and $\eta$ and/or did not

* Isospin symmetry justifies the assumption: $\pi^0 \approx (\pi^+ + \pi^-)/2$. 

Figure 8. Ratio of total charged hadron over pion spectra in p+p collisions at ISR energies ($\sqrt{s} = 21, 31, 44, 53$, and 63 GeV [47]). The straight line is at $h^\pm/\pi = 1.6$. 


subtract the direct photon component from the experimentally measured “unresolved” \( \pi^0 \) spectra. In order to do a meaningful comparison and average of all \( \pi^0 \) data sets, one needed therefore to subtract each one of these experimental “contaminations” from the published data tables.

\[ \text{ISR pion spectra } @ s = 62.4 \text{ GeV} \]

- \( p+p \rightarrow \pi^0 + X \) at 62.4 GeV -- CMOR [angelis89]
- \( p+p \rightarrow \pi^0 + X \) at 63 GeV -- AFS [akesson88]
- \( p+p \rightarrow \pi^0 + X \) at 62.8 GeV -- R-806 [kourkou80]
- \( p+p \rightarrow \pi^0 + X \) at 62.4 GeV -- CCOR [angelis78]
- \( p+p \rightarrow \pi^0 + X \) at 63 GeV -- CSZ [clark78]
- \( p+p \rightarrow \pi^0 + X \) at 62.4 GeV -- R-806 [kourkou79]
- \( p+p \rightarrow \pi^0 + X \) at 63 GeV -- SFM [drijard82]
- \( p+p \rightarrow \pi^0 + X \) at 62 GeV -- Saclay [banner77]
- \( p+p \rightarrow \pi^0 + X \) at 62 GeV -- Brit.-Scand. [alper75]
- \( p+p \rightarrow \pi^0 + X \) at 62 GeV (n = 0.25) -- CDHW [breakstone95]
- \( p+p \rightarrow \pi^0 + X \) at 62 GeV (n = 1.6) -- CDHW [breakstone95]
- \( p+p \rightarrow \pi^0 + X \) at 63 GeV (n = 0) -- SFM [akesson82]

**Figure 9.** Ratio of all experimental measurements reported in Table 1 over the final \( p+p \rightarrow \pi^0 \) parametrization (Eq. (2)). The upper plot shows the data as originally published whereas the lower panel shows the corrected data as described in the text. The error bars for each data set include (in quadrature) the original point-to-point, systematic and normalization uncertainties.
II.2.1. Center-of-mass energy correction: CERN ISR was a collider with proton beams crossing (and colliding) with a non-null angle depending on the experimental runs and setups. This fact resulted in differences in the effective available energy in the center-of-mass as large as $\sim 1\text{ GeV}$ (from $\sqrt{s} = 62$ to 63 GeV). RHIC Au+Au collisions were instead performed at a fixed $\sqrt{s_{NN}} = 62.4\text{ GeV}$. Fig. 10 shows the perturbative ratio of $\pi^0$ cross-sections as a function of $p_T$ for $p+p$ collisions at $\sqrt{s} = 62$ and 63 GeV over those at $\sqrt{s} = 62.4\text{ GeV}$ as given by NLO calculations [53]. Whereas the effect on the yields is minimal ($\lesssim 5\%$) for $p_T < 8\text{ GeV}/c$, the difference in yields monotonically increases with $p_T$ reaching a maximum of $\sim 10\%$ at the highest measured $p_T$ values at ISR. We corrected the yields of all data sets indicated in the last column of Table II using a simple second-order polynomial $p_T$ fit of the computed pQCD ratio.

**Figure 10.** Perturbative ratios of $p+p \rightarrow \pi^0$ yields vs. $p_T$ at two different center-of-mass energies ($\sqrt{s} = 63\text{ GeV}$, upper curve, and 62 GeV, lower curve) over the yields at $\sqrt{s} = 62.4\text{ GeV}$, as given by NLO pQCD calculations [53] (note that any uncertainties in the PDFs and/or FFs basically cancel out in the ratio).

II.2.2. Direct photon subtraction: Direct $\gamma$ were discovered in $p+p$ at CERN-ISR in 1979 [54], therefore before this date any high-$p_T$ photon-like cluster detected in the electromagnetic calorimeters was “identified” as a neutral pion. Figure 11 shows the direct-$\gamma/\pi^0$ ratio as a function of $p_T$ measured at $\sqrt{s} \approx 62.4\text{ GeV}$ by three ISR experiments (squares) [54, 55, 45] compared to the NLO pQCD ratio (circles) computed with CTEQ6 PDF and for three different (factorization-renormalization) scales (the theoretical points are centered at $\mu = p_T$ and the “errors” correspond to $\mu = p_T/2 - 2p_T$) [53, 56]. The prompt photon “contamination” is marginal below $\sim 4\text{ GeV}/c$, but it accounts for $\sim 1/3$ of the $\pi^0$ yield at $p_T \sim 10\text{ GeV}/c$, and equals it at $\sim 14\text{ GeV}/c$. 

The agreement data–theory is good and allows us to extrapolate the ratio to \( p_T \) values higher than those measured in [54, 55, 45]. The combined experimental and theoretical data points have been thus fitted to a 4th order polynomial (black curve) as a function of \( p_T, R_{\gamma/\pi^0}(p_T) \), with parameters: \( p_0 = 4.55\times10^{-2}, p_1 = -6.04\times10^{-2}, p_2 = 2.51\times10^{-2}, p_3 = -2.53\times10^{-3} \) and \( p_4 = 1.03\times10^{-4} \). The corrected \( \pi^0 \) yields, \( Y_{\pi^0}(p_T) \), were obtained from the “unresolved” \( \pi^0 \) yields, \( Y_{\pi^0+\gamma}(p_T) \), via: \( Y_{\pi^0} = Y_{\pi^0+\gamma} \cdot R_{\gamma/\pi^0}^{-1}/(1 + R_{\gamma/\pi^0}^{-1}) \), for those data sets listed in the 11th column of Table 1.

![Figure 11. Ratio of \( \gamma/\pi^0 \) cross-sections in p+p collisions at \( \sqrt{s} \approx 62.4 \) GeV as a function of \( p_T \) measured experimentally [54, 55, 45] (squares), and computed in NLO pQCD (circles, with error bars covering the range of theoretical scale uncertainties: \( \mu = p_T/2 - 2p_T \)) [56]. The black curve is a fit of the experimental and theoretical results to a common 4th order polynomial.](image)

**II.2.3. \( \eta \rightarrow \gamma\gamma \) subtraction:** Many of the “unresolved” \( \pi^0 \) measurements at ISR assumed that all detected electromagnetic clusters at high \( p_T \) were (merged) photons from the \( \pi^0 \) decay and neglected any possible contribution from the 2-gamma decay channel of the \( \eta \) meson (BR \( \eta \rightarrow \gamma\gamma = 0.394 \)). At high \( p_T \) (\( p_T > 1.5 \) GeV/c), however, the \( \eta/\pi^0 \) ratio is \( R_{\eta/\pi^0} = 0.46 \) (see the “world” compilation in Fig. 12). Those “unresolved” \( \pi^0 \) spectra listed in (the 12th column of) Table 1 have been scaled down by a factor of 0.82 above \( p_T = 1.5 \) GeV/c to take into account the \( \text{BR}_{\eta \rightarrow \gamma\gamma} \cdot R_{\eta/\pi^0} = 0.394 \cdot 0.45 = 0.18 \) \( \eta \) contamination [Note that such \( \sim 18\% \) factor was mentioned in some of the original papers (e.g. [37, 38]) but not actually subtracted from the tabulated results].
II.2.4. Final parametrization: After correction of the experimental spectra as described in the previous sections, there remained still a few outliers measurements that were (partially or totally) inconsistent (beyond $\sim 1.5\sigma$) with the rest of the data (see lower panel of Fig. 9). Three data sets: Drijard et al. [49] (charged pions measured off central rapidity, at 50°), Eggert et al. [39] and Busser et al. [37] were excluded of the final global fit analysis. Fig. 13 shows all the (corrected) pion data sets plotted as a function of $p_T$ compared to a common (purely empirical) 5-parameter functional form:

$$E d^3 \sigma_{pp \rightarrow \pi X} / d^3 p = A (e^{ap_T^2 + bp_T} + p_T/p_0)^{-n},$$

with parameters: $A = 265.1$ [mb GeV$^{-2}c^3$], $a = -0.0129$ [GeV$^{-1}c$], $b = 0.04975$ [GeV/$c$], $p_0 = 2.639$ [GeV/$c$], and $n = 17.95$. Eq. (2) provides a very good reproduction of the full spectral shape in the range $p_T = 0 - 16$ GeV/$c$. Above $p_T \approx 8$ GeV/$c$ the data (and the fit) have an exponential-like shape. This departure from the pure power-law behaviour expected for parton-parton scatterings is due to the fact that such large $p_T$ values are in a kinematical domain above $\langle x_T \rangle \approx 0.3$ and $\langle z \rangle \approx 0.8$ (see Fig. 15, right) where both the parton distribution functions (PDFs) and fragmentation functions (FFs) resp. start to decrease due to phase space boundaries (PDFs and FFs reach zero at the kinematical limit: $p_T \approx 30$ GeV/$c$). Such a change in the $p_T$ shape is confirmed also by pQCD calculations (see Fig. 15).

Figure 14 shows the ratio of the (selected and corrected) experimental pion spectra over the final $p+p \rightarrow \pi^0 + X$ parametrization in the same $p_T$ range ($p_T = 1 - 8$ GeV/$c$)

Mind that this is a purely empirical fit whose validity beyond the considered $p_T$ range is not guaranteed.
Relevance of baseline hard p+p spectra for high-energy A+A physics

Figure 13. Compilation of all pion transverse spectra measured in p+p collisions at \( \sqrt{s} \approx 62.4 \) GeV and fitted to a common function, Eq. (2), with the parameters quoted in the text.

covered by the PHENIX Au+Au \( \rightarrow \pi^0 + X \) data at RHIC. All p+p cross-sections are consistent with the final fit within their associated errors. The dashed lines indicate the \( \pm 25\% \) systematic uncertainty assigned to the reference. The gray thick line is the PHENIX charged-hadron reference (see Section II.1) divided by the expected \( h^\pm/\pi^0 = 1.6 \pm 0.16 \) ratio at \( p_T > 1.5 \) GeV/c (see Fig. 8). The \( \pm 0.16 \) errors of the \( h^\pm/\pi \) ratio are shown as dashed gray lines. The additional systematic 25\% error in the \( h^\pm \) reference is not plotted.
Relevance of baseline hard p+p spectra for high-energy A+A physics

Figure 14. Ratio of the selected and corrected $\pi^0,\pm$ and (scaled) $h^\pm$ measurements at CERN-ISR over the final $\pi^0$ parametrization (Eq. (2) with fit parameters reported in the text) as a function of $p_T$. The gray line is the charged-hadron reference spectrum (Section II.1), divided by $h^\pm/\pi = 1.6 \pm 0.16$ (The errors of the $h^\pm/\pi$ ratio are shown as dashed gray lines. There is an additional systematic 25% error in the $h^\pm$ reference not plotted).

Figures 15-16 show a comparison of the empirical $\pi^0$ parametrization to NLO pQCD predictions from W. Vogelsang [53] with fixed PDFs (CTEQ6), 2 different sets of fragmentation functions (Kniehl-Kramer-Pötter KKP [58] and Kretzer [59]) and 3 (factorization-renormalization-fragmentation) scales. The general shape and overall magnitude of the $p_T$ spectrum is well reproduced by the theoretical calculations (the fit is well contained within the theoretical limits given by $\mu = p_T/2 - 2p_T$). KKP FFs seem to reproduce better the magnitude of the cross-section, and the scale $\mu = p_T$ provides the best agreement with the data, especially above $p_T \approx 5$ GeV/c. Below $p_T \approx 5$ GeV/c all NLO spectra tend to consistently underpredict the observed $\pi^0$ cross-section. Such a discrepancy is also observed in high $p_T$ hadro-production at lower $\sqrt{s}$ [60] where soft-gluon resummation corrections [61] and additional non-perturbative effects (e.g. intrinsic $k_T$ [62]) must be introduced to bring parton model analyses into accord with data.
Relevance of baseline hard p+p spectra for high-energy A+A physics

Figure 15. Left: Comparison of the final empirical \( p+p \rightarrow \pi^0 + X \) parametrization at \( \sqrt{s} = 62.4 \text{ GeV} \) (solid curve) to NLO pQCD calculations [53] for 2 sets of FFs (KKP [58] and Kretzer [59]) and 3 different scales \( \mu = p_T/2, p_T, 2p_T \). Right: Scaling variables \( \langle x_{1,2} \rangle \) (average parton fractional momentum) and \( \langle z \rangle \) (average momentum fraction of the parent parton carried by the leading pion) for \( p+p \rightarrow \pi^0 \) (\( \sqrt{s} = 62.4 \text{ GeV} \)) at mid-rapidity versus the \( \pi^0 \) momentum, computed in perturbative QCD [28].

Figure 16. Ratio of the NLO pQCD predictions for inclusive \( p+p \rightarrow \pi^0 + X \) production at \( \sqrt{s} = 62.4 \text{ GeV} \) (Fig. 15) over the final empirical \( \pi^0 \) parametrization (Eq. 2 with the fit parameters reported in the text) as a function of \( p_T \).
II.3. Nuclear modification factor at $\sqrt{s_{NN}} = 62.4$ GeV:

Figure 17 shows the preliminary nuclear modification factor, Eq. (1), for high $p_T$ $\pi^0$ production in 0-10% central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV [34] obtained using: (i) the p+p $\pi^0$ reference Eq. (2) (red circles), and (ii) the p+p $h^\pm$ reference (see Section II.1) divided by the expected $h^\pm/\pi^0 = 1.6$ ratio (open circles). [For complementary info, the average Glauber number of NN collisions is $\langle N_{coll} \rangle = 845.4 \pm 140$ for a p+p inelastic cross-section at $\sqrt{s} = 62.4$ GeV of $\sigma_{inel} = 35.6 \pm 0.5$ mb obtained from the weighted average values of the total [63, 64, 65, 66, 68, 67, 69] ($\sigma_{tot} = 43.37 \pm 0.17$ mb) and elastic [66, 69] ($\sigma_{el} = 7.75 \pm 0.10$ mb) cross-sections measured at CERN-ISR]. Both $R_{AA}$ are compared to parton energy loss predictions for the quenching factor in a system with effective gluon densities $dN_g/dy = 650 – 800$ [70]. At intermediate $p_T \approx 2 \sim 5$ GeV the use of one or the other parametrization results in differences as large as $\sim 25\%$ in the amount of the suppression. Those divergences are indicative of the systematic uncertainty of the obtained p+p baseline references at $\sqrt{s} = 62.4$ GeV. Clearly a dedicated RHIC proton-proton run at this collision energy would help to reduce these uncertainties and better constrain the theoretical predictions of the excitation function of the high $p_T$ suppression [70, 74, 72, 73].

![Figure 17. Preliminary PHENIX nuclear modification factor, $R_{AA}(p_T)$, for $\pi^0$ measured in central Au+Au at 62.4 GeV [34] obtained using the p+p $\rightarrow \pi^0 + X$ (red circles) and p+p $\rightarrow h^\pm + X$ (open circles) references discussed in the text, compared to theoretical predictions for parton energy loss in a dense medium with $dN^g/dy = 650 – 800$ [70].](image-url)
Case III: $p+p \rightarrow \gamma + X$ reference at $\sqrt{s} = 200$ GeV

Thermal (real or virtual) photons emitted in high-energy A+A reactions provide direct information on the thermodynamical properties of the radiating underlying QCD matter and have long been considered privileged signatures of QGP formation \[74\]. Direct photons, defined as real photons not originating from the decay of final hadrons, are emitted at various stages of a A+A reaction. Three qualitatively different mechanisms are usually considered: (i) prompt $\gamma$ (“pre-equilibrium” or “pQCD”) emission from perturbative parton-parton scatterings in the first tenths of fm/c of the reaction, and (ii) subsequent emission from the thermalized partonic (QGP) and (iii) hadronic (hadron gas, HG) phases of the reaction. The partonic diagrams contributing in leading-order to photon production are $qg$-Compton and $q\bar{q}$-annihilation (Fig. 18) and collinear $q, g$ fragmentation (Fig. 19).

![Figure 18. Compton and annihilation diagrams for direct photon production in parton-parton scatterings.](image)

![Figure 19. Fragmentation (or “bremsstrahlung”) diagrams for direct photon production in parton-parton scatterings.](image)

The expected photon spectrum from Au+Au reactions at $\sqrt{s_{NN}} = 200$ GeV, can thus be obtained theoretically by combining: (i) NLO pQCD calculations for the primordial (hard) production (perturbative $p+p$ yields \[56\] scaled by the nuclear overlap function $T_{AA}$), plus (ii) hydrodynamical calculations of the space-time evolution of the reaction \[75\] \[76\] \[77\] complemented with modern parametrizations of the QGP \[78\] and HG \[76\] photon emission rates. Such calculations indicate that QGP thermal emission should be visible in a window of the inclusive direct photon spectrum between $p_T \approx 1 - 3$ GeV/c (Fig. 20).
Relevance of baseline hard p+p spectra for high-energy A+A physics

Figure 20. Expected thermal and prompt photon spectrum for central Au+Au reactions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) as given by a hydrodynamical model calculation \cite{77} complemented with pQCD yields for the prompt \( \gamma \) \cite{56}.

However, unfortunately, this range of transverse momenta potentially presents difficulties for the extraction of the thermal component. Indeed, perturbative QCD calculations indicate (Fig. 21) that below \( p_T \approx 3 \text{ GeV}/c \), prompt photons are mainly produced via the parton bremsstrahlung mechanism ("anomalous" component) \cite{56} [At increasingly high \( p_T \), prompt photon production is dominated by the purely perturbative production mechanisms (Compton and annihilation, Fig. 18) but still \( \sim1/4 \) of the total \( \gamma \)'s appear to come from jet fragmentation (diagrams depicted in Fig. 19) in these calculations]. Such a component should be depleted in central Au+Au at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) due to the same final-state QCD medium effects that result in the observed factor of \( \sim4–5 \) suppression of high \( p_T \) hadroproduction. To get a handle on the possible effect of parton energy loss in the total prompt photon spectrum we plot in Fig. 22 the "photon nuclear modification factor", \( R_{\gamma AA}(p_T) \), for central Au+Au estimated simply assuming that the suppression factor for the \( \gamma \)-fragmentation component is the same as that observed for high \( p_T \) hadrons, i.e. \( R_{\gamma AA}^{\gamma\text{frag}} = R_{\gamma AA}^{\text{high } p_T \pi^0} \approx 0.25 \). We determine \( R_{\gamma AA}^\gamma = [Ed\sigma_{\gamma\text{tot}}/dp - 0.75 Ed\sigma_{\gamma\text{frag}}/dp]/[Ed\sigma_{\gamma\text{tot}}/dp] \) with the same NLO yields \cite{56} used in Figure 21.

Figure 22 indicates that one should expect a moderate \( \sim30\% \) effective suppression of the total inclusive high \( p_T \) photon spectra due to parton energy losses in the dense medium\( \dagger\dagger \). This estimate is consistent with more involved calculations of the same

\( \dagger\dagger \)Note that in this estimate we have not considered partially counteracting (small) effects such as "Cronin enhancement" \cite{79} and Au PDF shadowing effects \cite{80}.

\( \dagger\dagger \)
Relevance of baseline hard p+p spectra for high-energy A+A physics

Figure 21. Relative contribution of different subprocesses of direct γ production versus $p_T$ in p+p collisions at $\sqrt{s} = 200$ GeV according to NLO pQCD: Compton+Annihilation diagrams (upper band) and fragmentation diagrams (lower band).

Figure 22. Nuclear modification factor, $R^\gamma_{AA}(p_T)$, for direct γ in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV assuming the same quenching factor for the jet-fragmentation photon component as observed for high $p_T$ hadrons ($R_{AA} \approx 0.25$).
Relevance of baseline hard $p+p$ spectra for high-energy $A+A$ physics

The suppression of the jet bremsstrahlung component could, therefore, partially “mask” the enhancement due to thermal photon emission in the range $p_T = 1 – 3$ GeV/$c$. Since the jet-fragmentation $\gamma$ component cannot be experimentally discarded via the standard “isolation” method due to the large soft background in Au+Au collisions, the only way to disentangle experimentally the counterbalancing effects of the thermal and quenched prompt $\gamma$ in Au+Au requires a detailed analysis of the $p+p$ reference:

(i) Measurement of isolated photons in $p+p$, $N_{pp \rightarrow \gamma_{isolated}}$, down to $p_T \approx 1$ GeV/$c$ with uncertainties $\lesssim 15\%$ provides a handle on the actual Compton+Annihilation reference production.

(ii) Measurement of total inclusive photons in $p+p$, $N_{pp \rightarrow \gamma_{total}}$, down to $p_T \approx 1$ GeV/$c$ with uncertainties $\lesssim 15\%$ provides a handle (since $N_{pp \rightarrow \gamma_{total}} = N_{pp \rightarrow \gamma_{isol}} + N_{pp \rightarrow \gamma_{fragm}}$) on the actual fragmentation $\gamma$ reference production.

(iii) Measurement of total inclusive $\gamma$ production in Au+Au, $N_{AuAu \rightarrow \gamma_{total}}$, down to $p_T \approx 1$ GeV/$c$ with uncertainties $\lesssim 15\%$.

(iv) The upper limit on thermal production for a given Au+Au centrality (with nuclear overlap function $T_{AA}$) is given by: $N_{\text{max}}^{AuAu \rightarrow \gamma_{thermal}} = N_{AuAu \rightarrow \gamma_{total}} - T_{AA} \cdot N_{pp \rightarrow \gamma_{isolated}}$.

(v) The lower limit on thermal production for a given Au+Au centrality (with nuclear overlap function $T_{AA}$) is given by: $N_{\text{min}}^{AuAu \rightarrow \gamma_{thermal}} = N_{AuAu \rightarrow \gamma_{total}} - T_{AA} \cdot N_{pp \rightarrow \gamma_{total}}$.

Figure 23 shows preliminary measurements by PHENIX of the total prompt photon production in $p+p$ \cite{31} [$N_{pp \rightarrow \gamma_{total}}$ in item (ii)] and in Au+Au \cite{32} [$N_{AuAu \rightarrow \gamma_{total}}$ in item (iii)] collisions at RHIC obtained by statistically subtracting the hadron decay-photon contributions ($\pi^0$, $\eta$, ...) from the total measured $\gamma$ spectrum. Within uncertainties, both results are consistent with the perturbative QCD expectations \cite{56}. A separation of the $p+p$ fragmentation-$\gamma$ component is under-way too \cite{33}. The main issue in order to experimentally resolve a possible thermal component in Au+Au is to measure with small uncertainties the prompt photon production below $p_T \approx 3$ GeV/$c$ (where the background of decay photons and (anti)baryon contaminations is more significant) in both colliding systems. Complementary methods to the statistical subtraction one (e.g. the measurement via $\gamma$ “conversion”), that are efficient for direct photon identification in the interesting range $p_T \approx 0.5 – 2$ GeV/$c$, are being currently pursued.

Summary

Three different cases of hard production in proton-proton collisions at three different center-of-mass energies, $\sqrt{s} \approx 20$, 62 and 200 GeV, have been discussed as benchmarks for the investigation of QGP signals in nucleus-nucleus collisions. High $p_T$ neutral pion production in central $A+A$ collisions at CERN-SPS ($\sqrt{s_{NN}} \approx 20$ GeV) has been found to be (slightly) suppressed compared to a parametrization of the $\pi^0$ cross-sections in $p+p$ collisions in free space. Such a result, possibly indicative of jet quenching effects...
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Figure 23. Left: Preliminary p+p → γ + X measured by PHENIX at √s = 200 GeV [53]. Right: Preliminary direct-γ excess measured by PHENIX at √s_{NN} = 200 GeV [5]. Both results are compared to NLO pQCD calculations [56].

at these energies, should be confirmed by a direct experimental measurement of high p_{T} p+p hadroproduction at √s ≈ 20 GeV. Secondly, high p_{T} π^{0} and h^{±} reference spectra at √s = 62.4 GeV have been constructed based on the weighted averaged of revised experimental data from CERN-ISR. Hard hadro-production is seen to be suppressed by up to a factor of ∼3 in central Au+Au collisions at RHIC at these collision energies. However, the current p+p references have p_{T} dependent uncertainties of order ∼25% precluding a detailed quantitative study of the excitation function of high p_{T} nucleus-nucleus suppression between SPS and RHIC energies. A dedicated RHIC p+p run at √s = 62.4 GeV would be needed to reduce such uncertainties and better constraint the theoretical models of parton energy loss in dense QCD matter. Finally, we have studied the possible effects of parton energy loss in the direct photon contribution of jet-fragmentation origin in Au+Au collisions at √s_{NN} = 200 GeV. Estimates based on NLO pQCD indicate that the nuclear modification factor can be reduced by ∼30% due to these effects, partially hiding the expected thermal photon emission from a radiating QGP. We have discussed how to get a handle on a possible thermal radiation Au+Au signal by detailed measurements of the isolated and non-isolated direct photon spectra in baseline p+p collisions at √s = 200 GeV.
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References

[1] See e.g. Karsch F 2002 Lect. Notes Phys. 583 209
[2] Collins J C, Soper D E and Sterman G 1985 Nucl. Phys. B 261 104
[3] d’Enterria D 2004 J. Phys. G 30, S767, Preprint nucl-ex/0404018
[4] NA50 Collaboration Bordalo P et al. 2003 Pramana 60 817
[5] PHENIX Collaboration Frantz J 2004 J. Phys. G 30, S1003, Preprint nucl-ex/0404006
[6] PHENIX Collaboration Adler S S 2004 et al., Preprint nucl-ex/0409028
[7] See review M. Gyulassy, I. Vitev, X.N. Wang and B.W. Zhang in Hwa R C (ed.) et al.: “Quark Gluon Plasma Vol. 3”, World Scientific, Preprint nucl-th/0302077
[8] PHENIX Collaboration Adcox K et al. 2002 Phys. Rev. Lett. 88 022301, Preprint nucl-ex/0109003
[9] STAR Collaboration Adler C et al. 2002 Phys. Rev. Lett. 89 202301, Preprint nucl-ex/0206011
[10] PHENIX Collaboration Adler S S et al. 2003 Phys. Rev. Lett. 91 072301, Preprint nucl-ex/0304022
[11] STAR Collaboration Adams J et al. 2003 Phys. Rev. Lett. 91 172302, Preprint nucl-ex/0305015
[12] PHOBOS Collaboration Back B B et al. 2004 Phys. Lett. B578 297, Preprint nucl-ex/0302015
[13] BRAHMS Collaboration Arsene I et al. 2003 Phys. Rev. Lett. 91 072305, Preprint nucl-ex/0307003
[14] PHENIX Collaboration Adler S S et al. 2003 Phys. Rev. Lett. 91 241803, Preprint hep-ex/0304038
[15] WA98 Collaboration Aggarwal M M et al. 2002 Eur. Phys. J. C 23 225 WA98 collaboration Aggarwal M M et al. 1998 Phys. Rev. Lett. 81 4087; [Erratum-ibid. 84 (2000) 578]
[16] Wang X N 1998 Phys. Rev. Lett. 81 2655
[17] Wang X N 2000 Phys. Rev. C61 064910; Wang E and Wang X N 2001 Phys. Rev. C64 034901
[18] Cronin J W et al. 1975 Phys. Rev. D11 3105
[19] Antreasyan D et al. 1979 Phys. Rev. D 19 764
[20] Straub P B et al. 1992 Phys. Rev. Lett. 68 452
[21] BCMOR Collaboration Angelis A L S et al. 1987 Phys. Lett. B 185 213
[22] d’Enterria D 2004 Phys. Lett. B 596, 32, Preprint nucl-ex/0403055
[23] Hagedorn R 1984 Riv. Nuovo Cim. 6N10 1
[24] Beier E W et al. 1978 Phys. Rev. D 18 2235
[25] Carey D C et al. 1976 Phys. Rev. D 14 1196
[26] Donaldson G et al. 1976 Phys. Rev. Lett. 36 1110
[27] FNAL E704 Collaboration Adams D L et al. 1996 Phys. Rev. D 53 4747
[28] Kretzer S 2004 hep-ph/0410219 and private communication
[29] Blattig S R et al. 2000 Phys. Rev. D 62 094030
[30] CERES/NA45 Collaboration Wurm J P and Bielcikova J 2004, Preprint nucl-ex/0407019 and Slivova J 2003 PhD thesis Charles University, Prague
[31] WA80 Collaboration Albrecht R et al. 1998 Eur. Phys. J. C5 255
[32] Vitev I and Gyulassy M 2002 Phys. Rev. Lett. 89 252301; and Vitev I 2004 J. Phys. G 30 S791
[33] Drees A 2004 private communication
[34] PHENIX Collaboration Busching H, these Proceeds., Preprint nucl-ex/0410002
[35] PHOBOS Collaboration Back B B et al. 2004, Preprint nucl-ex/0405003
[36] STAR Collaboration Xu Z B, Preprint nucl-ex/0411001
Relevance of baseline hard p+p spectra for high-energy A+A physics

[37] Busser F W et al. 1973 Phys. Lett. B 46 471
[38] Busser F W 1975 et al., Phys. Lett. B 55 232
[39] Eggert K et al. 1975 Nucl. Phys. B 98 49
[40] Busser F W et al. 1976 Nucl. Phys. B 106 1
[41] Clark A G et al. 1978 Phys. Lett. B 74 267
[42] CCOR Collaboration Angelis A L S et al. 1978 Phys. Lett. B 79 505
[43] Kourkoumelis C et al. 1979 Phys. Lett. B 83 257, and 1979 Phys. Lett. B 84 271
[44] C. Kourkoumelis C et al. 1980 Z. Phys. C 5 95
[45] CMOR Collaboration Angelis A L S et al. 1989 Nucl. Phys. B 327 541
[46] AFS Collaboration T. Akesson et al. 1990 Sov. J. Nucl. Phys. 51 836 [Yad. Fiz. 51 1314]
[47] AFS Collaboration A. L. S. Angelis et al. 1990 Nucl. Phys. B 335 261
[48] Kniehl B A, Kramer G and Potter B. 2001 Nucl. Phys. B 597, 337
[49] Kretzer S 2000 Phys. Rev. D 62, 054001
[50] Bourrely C and Soffer J, 2004 Eur. Phys. J. C 36 371, Preprint hep-ph/0311110
[51] Gordon L E and Vogelsang W 1993 Phys. Rev. D 48 3136, 1994 Phys. Rev. D 50 1901, and Vogelsang W (private communication).
[52] Amaldi U et al. 1977, Phys. Lett. B 66 390
[53] Amaldi U et al. 1978, Nucl. Phys. B 145 367
[54] Baksay L et al. 1978, Nucl. Phys. B 141 1 [Erratum-ibid. 1979 B 148 538]
[55] CERN-Naples-Pisa-Stony Brook Collaboration Ambrosio M et al. 1982 Phys. Lett. B 113 347
[56] Carboni G et al. 1985 Nucl. Phys. B 254 697
[57] Amos N et al. 1985 Nucl. Phys. B 262 889
[58] Vitev I 2004 Preprint nucl-th/0404052
[59] Adil A and Gyulassy M 2004 Phys. Lett. B 602 52
[60] Wang X N 2004 Phys. Rev. C 70 031901
[61] Dainese A, Loizides C and Paic G 2004 Preprint hep-ph/0406201
[62] See e.g. Peitzmann T and Thoma M H 2002 Phys. Rept. 364 175; and Gale C and Haglin K L 2003 in “Quark Gluon Plasma Vol 3”, World Scientific, Singapore, Preprint hep-ph/0306098
[63] PHENIX Collaboration Okeda K 2004 Proceeds. SPIN’04