Is q̂ a physical quantity or just a parameter?
and other unanswered questions in High-p_T Physics

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Abstract. The many different theoretical studies of energy loss of a quark or gluon traversing a medium have one thing in common: the transport coefficient of a gluon in the medium, denoted $\hat{q}$, which is defined as the mean 4-momentum transfer[2], q^2, by a gluon to the medium per gluon mean free path, λ_{mfp}. In the original BDMPSZ formalism, the energy loss of an outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, due to coherent gluon bremsstrahlung is proportional to the q^2 and takes the form:

$$\frac{-dE}{dx} \simeq \alpha_s \left\langle q^2(L) \right\rangle = \alpha_s \, \mu^2 \, L/\lambda_{\mathrm{mfp}} = \alpha_s \, \hat{q} \, L \qquad , \qquad (1)$$

where μ, is the mean momentum transfer per collision. Thus, the total energy loss in the medium goes like L^2.

Additionally, the accumulated momentum[2], $\left\langle k_\perp^2 \right\rangle$, transverse to a gluon traversing a length L in the medium is well approximated by $\left\langle k_\perp^2 \right\rangle \approx \left\langle q^2(L) \right\rangle = \hat{q} L$. A simple estimate shows that the $\left\langle k_\perp^2 \right\rangle \approx \hat{q} L$ should be observable at RHIC at $\sqrt{s_{NN}} = 200$ GeV via the broadening of di-hadron azimuthal correlations resulting in an azimuthal width $\sim \sqrt{2}$ larger in Au+Au than in $p+p$ collisions . Measurements relevant to this issue will be discussed as well as recent STAR jet results presented at QM2014.

Other topics to be discussed include the danger of using forward energy to define centrality in $p(d)$+A collisions for high p_T measurements, the danger of not using comparison $p+p$ data at the same $\sqrt{s}$ in the same detector for R_{AA} or lately for R_{pA} measurements. Also, based on a comment at last year's 9th workshop that the parton energy loss is proportional to $dN_{\mathrm{ch}}/d\eta$, new results on the dependence of the shift in the p_T spectra in A+A collisions from the T_{AA}-scaled $p+p$ spectrum (to be discussed in detail in another presentation) will be shown.

1. Introduction–BDMPSZ, the first QCD based Jet Quenching Model

I don't want to discuss models in detail, since they are nothing like QED or QCD—theories that you can set your watch by (at least QED). I concentrate on one example, the first QCD based model [1] which stimulated the use of hard-probes at RHIC as a signature of the QGP.

It is important to note that the original STAR Letter of Intent (LBL-29651) in 1990, following Wang and Gyulassy (LBL-29390), did cite as one objective: "the use of hard scattering of partons as a probe of high density nuclear matter... Passage through hadronic or nuclear matter is predicted to result in an attenuation of the jet energy and broadening of jets. Relative to this damped case, a QGP is transparent and an enhanced yield is expected."

Of course this is precisely the opposite of what was actually discovered at RHIC. Furthermore, what had been observed in A+A and p+A collisions was an enhancement of the hard scattering, a.k.a. the Cronin Effect [2], rather than an attenuation. Thus, until the appearance of the fully QCD based models, starting with BDMPS [3], I described the original Plümer-Gyulassy-Wang [4, 5] Jet Quenching as "the vanishing of something that doesn't exist in the first place", namely the attenuation of hard-scattering in dense but confined nuclear matter (CNM).

In the early c. 1990 publications [4, 6] the QGP effect was thought to be "a sudden *decrease* of dE/dx near the quark-gluon plasma phase transition" which could *reduce* the CNM Jet Quenching ("unquench the jets" [6]) and thus be a possible signature of the QGP. This idea was downplayed between the original STAR letter of intent in September 1990 and the update in July 1991 as reflected in the new goal for Parton Physics: "For example, it has been suggested that there will be observable changes in the energy loss of propagating partons as the energy density of the medium increases, particularly if the medium passes through a phase transition to the QGP [7]".

The reason for the downplaying of jet quenching as a possible probe of the QGP by STAR in 1991 was the discovery [7] that instead of small dE/dx in the QGP it was "recently found that at least deep in the QGP phase, the induced radiative energy loss could be quite large" [7]. Subsequent work found that the radiation was suppressed by the LPM effect [8] which led to a series of developments, nicely reviewed in Ref. [1], that eventually led to the BDMPSZ QCD based model [1].

1.1. The real QGP jet quenching and the importance of attending conferences

I first heard about the original CNM Jet Quenching [4] at an excellent meeting in Strasbourg in October 1990 [9] to discuss "Quark-Gluon Plasma Signatures" in a talk by Michael Plümer that was greeted with disbelief by the many CERN-ISR veterans who had puzzled over the Cronin effect for many years. This led to my description noted a few paragraphs above. Meanwhile, the RHIC experiments and ALICE at the LHC [10] were designed with a focus on J/Ψ suppression [11] as the gold-plated signature for deconfinement and the QGP.

In 1998 at the QCD workshop in Paris [12], I found what I thought was a cleaner signal of the QGP when Rolf Baier asked me whether jets could be measured in Au+Au collisions because he had made studies in pQCD [3] of the energy loss of partons, produced by hard-scattering "with their color charge fully exposed", in traversing a medium "with a large density of similarly exposed color charges". The conclusion was that "Numerical estimates of the loss suggest that it may be significantly greater in hot matter than in cold. *This makes the magnitude of the radiative energy loss a remarkable signal for QGP formation*" [1]. In addition to being a probe of the QGP, the fully exposed color charges allow the study of parton-scattering with $Q^2 \ll 1-5$ (GeV/c)^2 in the medium where new collective QCD effects may possibly be observed.

Because the expected energy in a typical jet cone $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV would be $\pi R^2 \times 1/2\pi \times dE_T/d\eta = R^2/2 \times dE_T/d\eta \sim 350$ GeV for $R = 1$, where the kinematic limit is 100 GeV, I said (and wrote [12]) that jets can not be reconstructed in Au+Au central collisions at RHIC—still correct after 16 years. On the other hand, hard-scattering was discovered in $p + p$ collisions at the CERN-ISR in 1972 with single particle and two-particle correlations, while jets had a long learning curve from 1977–1982 with a notorious false claim (e.g. see Refs. [13, 14]), so I said (and wrote [12]) that we should use single and two-particle measurements at RHIC—which we did and it WORKED! The present solution for jets in A+A collisions (LHC 2010 and RHIC c.2014) is to take smaller cones, with 100 GeV in $R = 0.54$, 56 GeV in $R = 0.4$, 32 GeV in $R = 0.3$, 14 GeV in $R = 0.2$ at RHIC.

1.2. $\hat{q}$ or di-jet broadening and gluon radiation

There are many different theoretical studies of energy loss of a quark or gluon with their color charges fully exposed passing through a medium with a large density of similarly exposed color charges (i.e. a QGP). The approaches are different, but the one thing that they have in common [15] is the transport coefficient of a gluon in the medium, denoted $\hat{q}$, which is defined as the mean 4-momentum transfer[2], q^2, by a gluon to the medium per gluon mean free path, λ_{mfp}. Thus the mean 4-momentum transfer[2] for a gluon traversing length L in the medium is, $\left\langle q^2(L) \right\rangle = \hat{q}\,L = \mu^2\,L/\lambda_{\mathrm{mfp}}$, where μ, the mean momentum transfer per collision, is "conveniently taken" [1] as the Debye screening mass acquired by gluons in the medium. In this, the original BDMPSZ formalism [1], the energy loss of an outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, due to coherent gluon bremsstrahlung is proportional to the 4-momentum[2] transferred to the medium and takes the form:

$$\frac{-dE}{dx} \simeq \alpha_s \left\langle q^2(L) \right\rangle = \alpha_s\,\hat{q}\,L = \alpha_s\,\mu^2\,L/\lambda_{\mathrm{mfp}} \qquad , \tag{2}$$

so that the total energy loss in the medium goes like L^2 [3].

Additionally the accumulated transverse momentum[2], $\left\langle k_\perp^2 \right\rangle$, for a gluon traversing a length L in the medium is well approximated by $\left\langle k_\perp^2 \right\rangle \approx \left\langle q^2(L) \right\rangle = \hat{q}\,L$. This leads to a remarkable relationship [1] between the energy loss and di-jet broadening ("acoplanarity [4]"):

$$\frac{-dE}{dx} \simeq \alpha_s \left\langle k_\perp^2 \right\rangle \qquad , \tag{3}$$

which is thought to be independent of the dynamics of the individual scatterings in pQCD and thus should be expected to hold equally in a finite length QGP and CNM [16]. A simple estimate shows that the $\left\langle k_\perp^2 \right\rangle \approx \hat{q}\,L$ should be observable at RHIC via the broadening of di-hadron azimuthal correlations. Assume that for a trigger particle with p_{T_t} the away-parton traverses slightly more than half the 14 fm diameter medium for central collisions of Au+Au , say 8 fm. With a $\hat{q} = 1$ GeV^2/fm [15], this would correspond to $\left\langle k_\perp^2 \right\rangle = \hat{q}\,L = 8$ (GeV/c)^2, compared to the measured [17] $\left\langle k_T^2 \right\rangle = 8.0 \pm 0.2$ (GeV/c)^2 for di-hadrons in $p + p$ collisions[2] with roughly the same p_{T_t} and p_T^{assoc}. This should be visible as a width of the p_T^{assoc} azimuthal distribution $\sim \sqrt{2}$ larger in Au+Au than in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

However, there is no direct evidence as yet for broadening of di-hadron or di-jet correlations from the effect of $\hat{q}$ in either d+Au [18] or Au+Au collisions at RHIC, where the principal difficulty in Au+Au stems from the systematic uncertanties due to the collective flow background of the medium, $v_2, v_3 \ldots v_n$ for di-hadron measurements; nor at LHC, where the very large jet $p_T \simeq 100$ GeV, for di-jet measurements, may have obscured this signal.

2. Discovery of the real QGP jet quenching, RHIC's main claim to fame.

The discovery at RHIC [19] that π^0's produced at large transverse momenta are suppressed in central Au+Au collisions by a factor of ~ 5 compared to pointlike scaling from p+p collisions is arguably *the* major discovery in Relativistic Heavy Ion Physics. For π^0 (Fig. 1a) [20] the hard-scattering in p+p collisions is indicated by the power law behavior p_T^{-n} for the invariant cross section, $Ed^3\sigma/dp^3$, with $n = 8.1 \pm 0.1$ for $p_T \geq 3$ GeV/c. The Au+Au data at a given p_T can be characterized either as shifted lower in p_T by $\delta p'_T$ from the pointlike scaled p+p data at $p'_T = p_T + \delta p'_T$, or shifted down in magnitude, i.e. suppressed. In Fig. 1b, the suppression of the many identified particles measured by PHENIX at RHIC is presented as the Nuclear Modification Factor, $R_{AA}(p_T)$, the ratio of the yield of e.g. π per central Au+Au collision

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[2] In both cases the azimuthal projection is only half the quoted $\left\langle k_T^2 \right\rangle$ or $\left\langle k_\perp^2 \right\rangle$
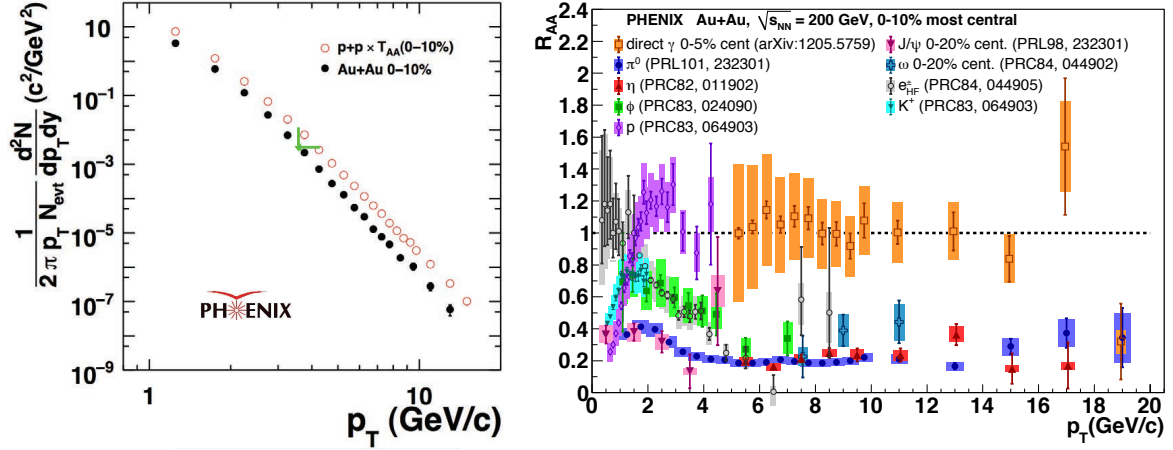
Figure 1. a) (left) Log-log plot of invariant yield of π^0 at $\sqrt{s_{NN}} = 200$ GeV as a function of transverse momentum p_T in $p+p$ collisions, multiplied by $\langle T_{AA} \rangle$ for Au+Au central (0–10%) collisions, compared to the Au+Au measurement [20]. Vertical arrow is for $R_{AA}(p_T)$, horizontal arrow for $\delta p_T'$. b) (right) $R_{AA}(p_T)$ for all identified particles so far measured by PHENIX in Au+Au central collisions at $\sqrt{s_{NN}} = 200$ GeV.

(upper 10%-ile of observed multiplicity) to the pointlike-scaled $p+p$ cross section at the same p_T, where $\langle T_{AA} \rangle$ is the average overlap integral of the nuclear thickness functions:

$$R_{AA}(p_T) = \frac{(1/N_{AA}) \; d^2 N_{AA}^\pi / dp_T dy}{\langle T_{AA} \rangle \; d^2 \sigma_{pp}^\pi / dp_T dy} \quad . \tag{4}$$

The striking differences and similarities of $R_{AA}(p_T)$ in central Au+Au collisions for the many particles measured by PHENIX (Fig. 1b) illustrate the importance of particle identification for understanding the physics of the medium produced at RHIC. Notable are that ALL particles are suppressed for $p_T > 4$ GeV/c (except for direct-γ which are not coupled to color), even electrons from c and b quark decay; with one notable exception: the protons are enhanced for $2 \leq p_T \leq 4$ GeV/c, called the baryon anomaly, although recently the same Cronin-like effect has been seen in $d+$Au collisions [21].

2.1. $\delta\mathbf{p_T'}/\mathbf{p_T'}$, the fractional shift in the $\mathbf{p_T'}$ spectrum
After more than a decade of using the ratio R_{AA}, we are now paying more attention to $\delta p_T'/p_T'$, the fractional shift of the p_T' spectrum, as an indicator of energy loss in the QGP Fig. 2 [22]. For a constant fractional energy loss, which is true at RHIC in the range $6 < p_T < 12$ GeV/c (as shown in Fig. 1a where the $p+p$ reference and Au+Au measurement are parallel on a log-log plot) there is a simple relationship between R_{AA}, $\delta p_T'/p_T'$ and n, the power in the invariant p_T spectra:

$$R_{AA}(p_T') = R_{AA}(p_T) = (1 - \delta p_T'/p_T')^{n-2} \quad . \tag{5}$$

Using $\delta p_T'/p_T'$ is important for comparison to the LHC measurements where the power is $n \approx 6$ compared to $n = 8.1$ at RHIC, so that the same R_{AA} does not mean the same $\delta p_T'/p_T'$. Strictly $\delta p_T'/p_T'$ is not a measure of the parton energy loss in the QGP but is used as a proxy. Figure 2a shows that $\delta p_T'/p_T'$ at $p_T' = 7$ GeV/c for RHIC and LHC both increase monotonically with centrality (N_{part}) but is a factor of 2 to 1.4 larger at LHC, depending on centrality, a likely indication of a hotter and/or denser medium. Figure 2b attempts to determine whether $\delta p_T'/p_T'$ is a universal function of the charged particle density, $dN_{\text{ch}}/d\eta$ at both RHIC and LHC, as suggested by Edward Shuryak at this meeting last year. The dependence is not quite universal.
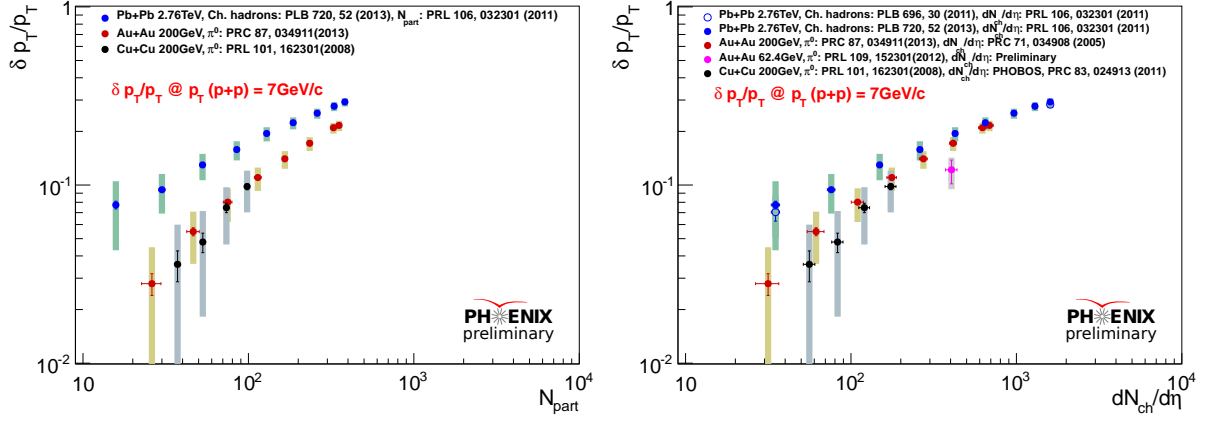
Figure 2. Plots from PHENIX [22] of $\delta p'_T/p'_T$ at $p'_T \equiv p_T(p + p) = 7$ GeV for π^0 (RHIC) and charged hadrons (LHC): a) as a function of centrality (N_{part}), b) as a function of $dN_{\mathrm{ch}}/d\eta$.

A fit of $\delta p_T/p_T \propto (dN_{\mathrm{ch}}/d\eta)^\alpha$ gives $\alpha \approx 0.35$ at LHC and 0.55 at RHIC, although the data at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV do appear to merge for $(dN_{\mathrm{ch}}/d\eta) \geq 300$. Hopefully, measurements of $\delta p_T/p_T$ will eventually lead to the determination of dE/dx of partons in the QGP.

3. STAR jet and jet-hadron measurements

3.1. Jet-hadron correlations as a proxy for di-jet broadening

Admittedly, measuring jets at RHIC at $\sqrt{s_{NN}} = 200$ GeV is much harder than at LHC at $\sqrt{s_{NN}} = 2.76$ TeV: the cross section in the relevant region is $\gtrsim 100$ times larger at LHC while the soft physics background is only a factor of 2 larger [23]. Nevertheless, the principal difficulty in observing the broadening of di-jet or di-hadron azimuthal correlations by the transport coefficient $\hat{q}$ of the QGP stems from artifacts with names such as "Mach Cone", "Ridge", "Head and Shoulders" which are now known to be due to the modulation of the soft physics background by collective flow with both even and odd harmonics [24]. Of course, understanding that the extra "bumps" in the correlation function are due to odd harmonics still requires one to know the values of these harmonics in order to subtract them. This is still the largest systematic uncertainty in attempts to observe the $\hat{q}$-broadening, for instance, the most recent attempt by STAR using jet-hadron correlations [25] (Fig. 3). When the full systematic uncertainties, including those
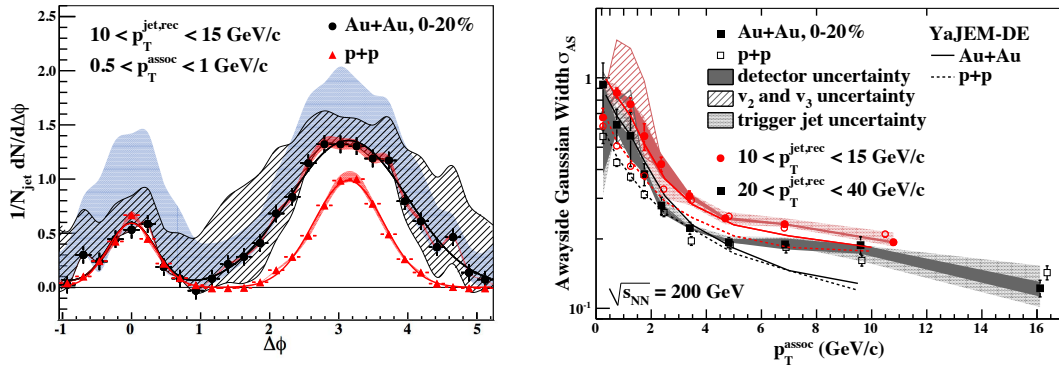

Figure 3. a) (left) Azimuthal correlation ($1/N_{\mathrm{jet}}dN/d\Delta\phi$) in Au+Au and $p+p$ with systematic uncertainties shown [25]. b)(right) Awayside rms width, σ_{AS}, as a function of p_{T_a} [25].

on v_2 and v_3 (Fig. 3a), are taken into account, the result for the medium induced broadening of the away-side widths, σ_{AS}, in Au+Au relative to $p + p$ (Fig. 3b) which looked significant in the preliminary results, as shown last year [26], become only "suggestive of medium-induced broadening [25]" in the final result because "they are highly dependent on the shape of the subtracted background [25]", notably the v_2 and v_3 of the trigger jets.

3.2. At last: jet measurements in Au+Au at RHIC in 2014?
Some interesting new jet measurements in Au+Au collisions at RHIC were presented at Quark Matter 2014 in a plenary review talk on jets by Yen-Jie Lee [27] who works on CMS. Figure 4 shows that the STAR charged jets in a cone with $R = 0.2$ have much less suppression ($R_{AA} \gg 0.3$) than π^0 ($0.2 \leq R_{AA} \leq 0.3$) in the range $10 < p_T < 20$ GeV.
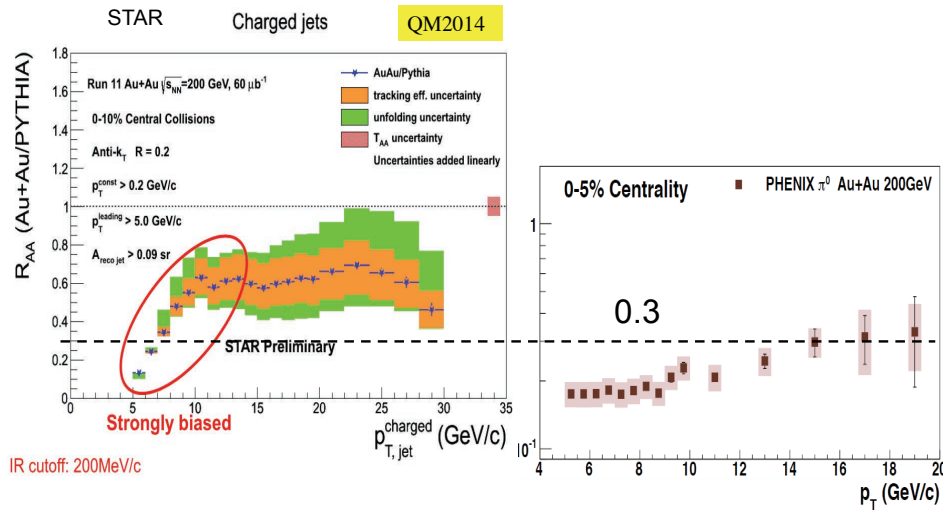

Figure 4. a) (left) STAR R_{AA} for charged jets at $\sqrt{s_{NN}} =$200 GeV in central Au+Au collisions (see details in legend) compared to b) R_{AA} for PHENIX π^0. The dashed line at 0.3 is the maximum R_{AA} for π^0 in this p_T range.

This is quite different from jets at the LHC (Fig. 5) which have comparable or smaller R_{AA} than charged particles from jet fragmentation in the range $30 < p_T < 100$ GeV. Note that the γ, W and Z^0 bosons in Fig. 5b which are not coupled to color are not suppressed.
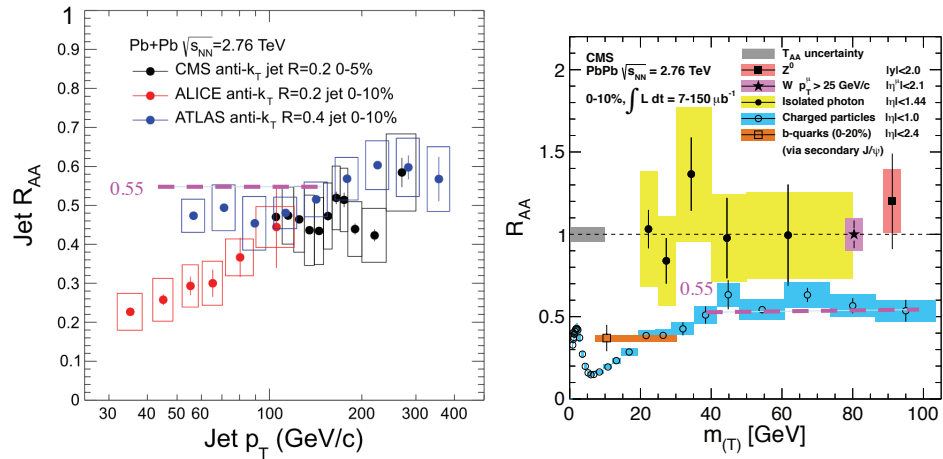

Figure 5. a) (left) R_{AA} for jets at $\sqrt{s_{NN}} =$2.76 GeV by CMS and ALICE compared to b) CMS R_{AA} for charged hadrons ($R_{AA} \approx 0.55$), b-quarks and 3 favorite Electro-Weak Bosons [27].

For STAR, the disagreement of the jet and single particle R_{AA} gets worse as the jet cone is increased from R=0.2 to 0.3 to 0.4 (Fig. 6). Some people would say that this is great because all the jet fragments and/or any energy lost in the QGP by the originating parton have been captured in the R=0.4 cone. Skeptics like myself can hardly wait to see what happens when the jet cone is further increased. After 14 runs at RHIC, the jet learning curve in Au+Au central collisions still has a way to go.
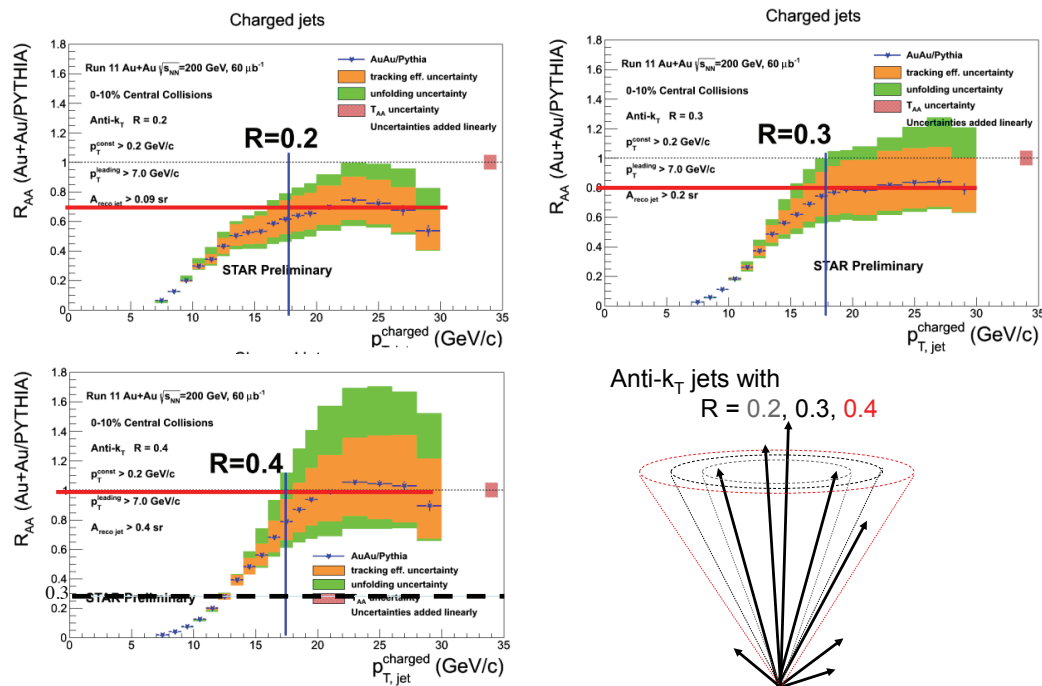

Figure 6. STAR R_{AA} for charged jets at $\sqrt{s_{NN}}$ =200 GeV in central Au+Au collisions for 3 different jet cones with $R = 0.2, 0.3, 0.4$ (see details in legend and sketch) [27].

The good news for the future is that a new detector, now called sPHENIX, to find jets by the more traditional method using hadron calorimetry has been proposed, is moving along on the approval process and is on the schedule at RHIC for partial commisioning in 2019.

4. Kari Eskola once asked me whether I believed in QCD

In the 4th meeting in this series, in Prague in 2009, Kari Eskola asked me whether I believed in QCD after I expressed doubt about some calculation. I answered, "Of course I believe in QCD; but I am skeptical of many calculations that claim to be QCD." Such calculations are still being made which I learned about by reading Jan Rak's talk at a recent conference [28].

4.1. Another wrong calculation claiming to be QCD

Figure 7a [29] shows a supposed QCD calculation of the inclusive jet cross section in $p + p$ collisions at $\sqrt{s_{NN}}$ =7–33 TeV in which the integrated inclusive jet cross section exceeds the inelastic cross section. This is normal for inclusive measurements, e.g. single particle spectra, where the integral of the inclusive cross section equals the interaction cross section times the mean multiplicity, but is well known not to happen in hard-scattering. Nature (i.e. non-perturbative QCD) finds a way to stop the $1/p_T{}^n$ divergence, which flattens for $p_T \lesssim 3$ GeV/c as shown for direct-γ production in Fig 7b. The same flattening happens for the p_T distribution of Drell-Yan lepton pair production [30]. Even though the authors of Pythia provided "a phenomenological modification of the low-p_T behiavior of the jet cross section" to agree with
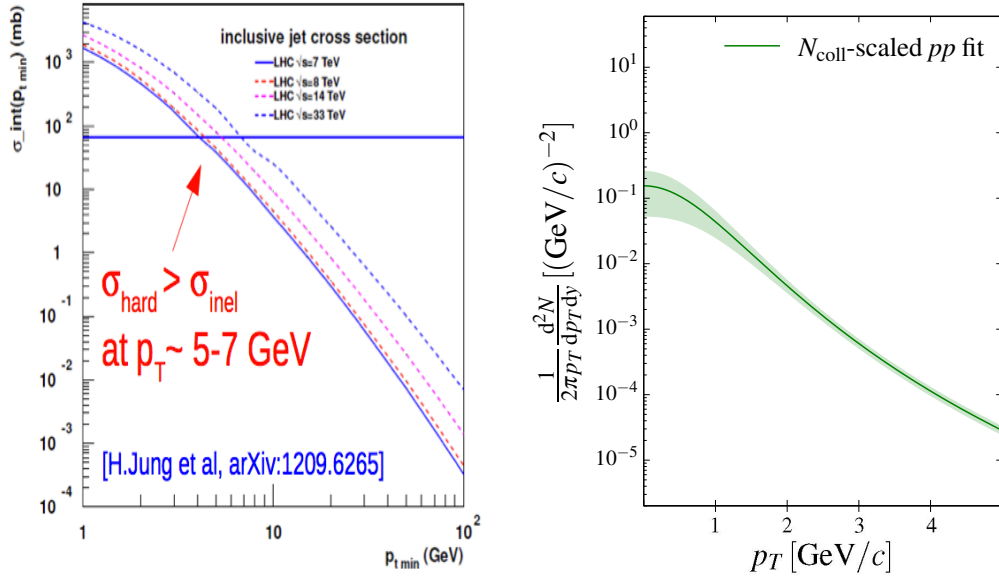
Figure 7. a) (left) Integrated inclusive jet cross section for $p_T \geq p_{T_{min}}$ as a function of $p_{T_{min}}$ from Ref. [29] for several $\sqrt{s_{NN}}$ indicated. b) (right) $(E d^3\sigma/dp^3)/(0.054 \text{ mb})$ for direct-γ production in $p+p$ collisions at $\sqrt{s} =$200 GeV. The distribution is scaled for comparison to Au+Au central (0-20%) measurements [31].

the actual QCD behavior, the Pythia 'calculators' [29] decided not to use it and got a ridiculous answer, once again confirming my response to Kari.

4.2. Direct-γ production, real QCD calculations and x_T scaling

My favorite QCD reaction is direct-γ production via the subprocess $g + q \rightarrow \gamma + q$. This is much better than jet production to test QCD calculations as well as to measure parton energy loss in the QGP for several reasons: i) the γ participates directly in the hard-scattering and then emerges freely and unbiased from the reaction, with no accompanying particles, and passes unaffected through the medium to a detector where its energy can be measured precisely; ii) the transverse momentum of the jet from the outgoing quark at the reaction point is equal and opposite to that of the γ, thus is also precisely known (modulo k_T); iii) for pQCD calculations of the direct-γ inclusive spectrum, no fragmentaton functions are needed—a major advantage over jet and single particle calculations. This is illustrated in Fig. 8 where x_T scaling is presented for both inclusive direct-γ (Fig. 8a) over a large range of $\sqrt{s}$ in $p + p$ and $\bar{p} + p$ collisions and for inclusive charged particles at 3 values of $\sqrt{s}$ (Fig. 8b).

x_T scaling [34, 35] provides a totally data driven test of whether pQCD or some other underlying subprocess is at work, without the need to know the details of the structure functions, fragmentation function and coupling constant, as well as providing a compact quantitative way to describe the data using the effective index, $n_{eff}(x_T, \sqrt{s})$. The invariant cross section for inclusive single particle production can be written as:

$$E\frac{d^3\sigma}{dp^3} = \frac{d^3\sigma}{p_T dp_T dy d\phi} = \frac{1}{p_T^{n_{eff}(x_T,\sqrt{s})}} F(x_T) = \frac{1}{\sqrt{s}^{n_{eff}(x_T,\sqrt{s})}} g(x_T) \qquad , \qquad (6)$$

where $E d^3\sigma/dp^3 = \sigma^{inv}(p_T, \sqrt{s})$ is the invariant cross section for inclusive particle production with transverse momentum p_T at c.m. energy $\sqrt{s}$, and $x_T = 2p_T/\sqrt{s}$. It is important to
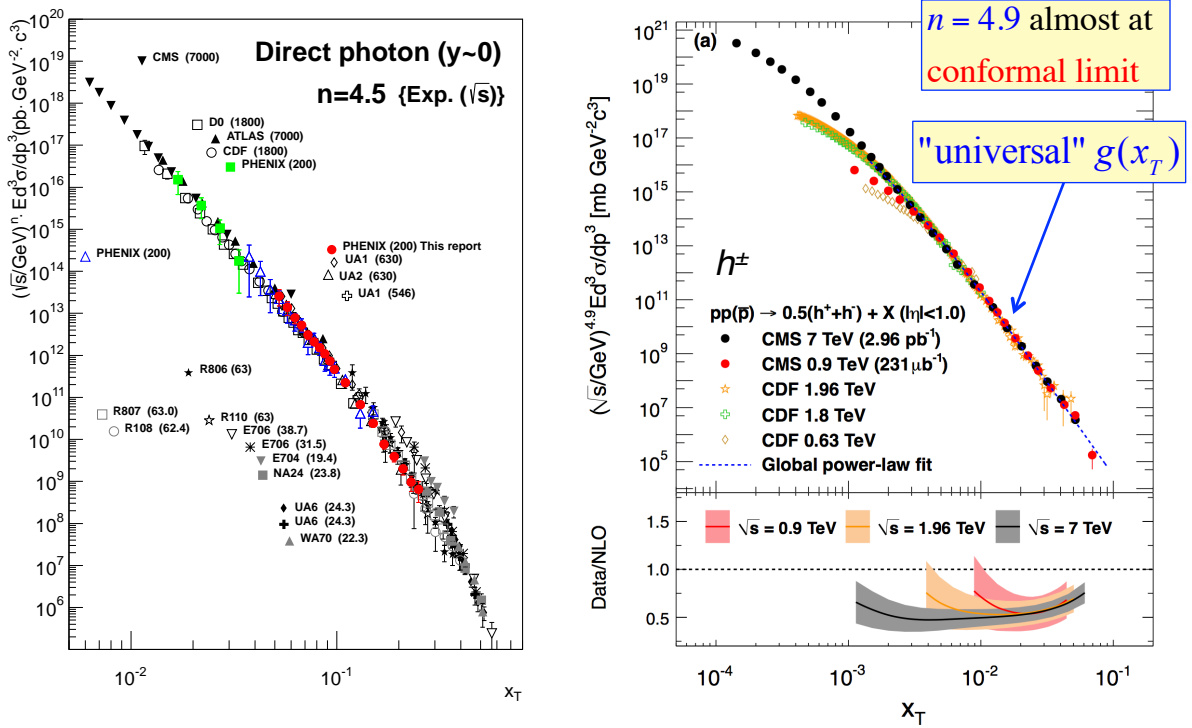
Figure 8. a) (left) Direct-γ measurements plotted as $\sqrt{s}^{\,n_{\mathrm{eff}}} \times Ed^3\sigma/dp^3$ at $x_T \equiv 2p_T/\sqrt{s}$ with $n_{\mathrm{eff}} = 4.5$ [32]. The legend gives the experiment and $\sqrt{s}$. b)(right) x_T scaling for inclusive charged particles [33].

emphasize that the effective power, $n_{\mathrm{eff}}(x_T, \sqrt{s})$, is different from the power n of the invariant cross section, which varies with $\sqrt{s}$ (which it must if x_T scaling is to hold). For pure vector gluon exchange, or without the evolution of α_s and the structure and fragmentation functions in QCD, $n_{\mathrm{eff}} = 4$ as in Rutherford scattering. However, due to the non-scaling in QCD [35], the measured value of n_{eff} depends on the x_T value and the range of $\sqrt{s}$ used.

The point of this discussion and Fig. 8 is that the direct-γ data are very well described by QCD and x_T scaling, with $n_{\mathrm{eff}} = 4.5$ due to the QCD evolution, while the charged particle data also follow x_T scaling very well, but with a larger $n_{\mathrm{eff}} = 4.9$ due to the added non-scaling of the fragmentation functions. This shows that the charged particle cros-sections follow QCD even though the NLO QCD calculations miss the data by a factor of 2, which [33] "suggests that the fragmentation functions are not well tuned for LHC energies."

5. Problems with centrality for reactions with very large p_T in p+A collisions

Last year [26], I discussed a problem (or excitement for some people) with determining the centrality in d+Au at RHIC, using Beam-Beam counters at forward rapidity, $3.1 < \eta < 3.9$, for reactions with very large $p_T > 10$ GeV/c ($x_T > 0.1$) at mid-rapidity. This year, similar methods at LHC for p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, produce a similar problem at the same x_T (Fig. 9a) [36]. Figure 9b [36] shows that at both LHC and RHIC, avoiding centrality cuts by using minimum bias collisions to measure $R_{\mathrm{pA}} = A^{\alpha-1}$ gives more reasonable results.[3] This is the basis for the p+A run at RHIC in 2015, using a few values of A to determine $\alpha(p_T)$ of minimum bias $p + A$ collisions rather than make centrality cuts.

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[3] I use the original Cronin terminology [2] here where the cross section for hard scattering in p+A collision was represented as $\sigma_{\mathrm{pA}}(p_T) = A^{\alpha} \times \sigma_{p+p}(p_T)$, where $\alpha \equiv 1$ for pure point-like scattering with no shadowing.
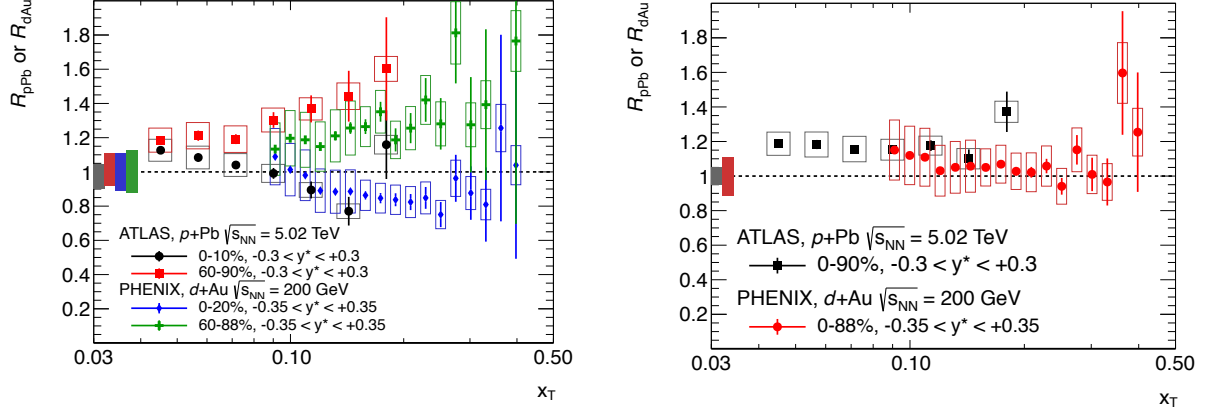
Figure 9. a) (left) $R_{\mathrm{p+Pb}}$ (LHC) and R_{dAu} (RHIC) for jets [36], at $\sqrt{s_{NN}}$ and centralities indicated. b)(right) Same for minimum bias collisions.

6. The importance of $p + p$ comparison data at the same $\sqrt{s}$ in the same detector

Two LHC experiments presented measurements this year of R_{pPb} from $p+\mathrm{Pb}$ collisions at $\sqrt{s_{NN}}$ =5.02 TeV from the run in 2013. It was an impressive tour-de-force for the LHC to collide particles with different Z/A in a single ring; but the price the experimenters paid was that they had no comparison $p + p$ data at the same $\sqrt{s}$. The results from the ALICE and CMS experiments are shown in Fig. 10. The ALICE results show $R_{\mathrm{pPb}} = 1$, constant for $10 \leq p_T \leq 50$
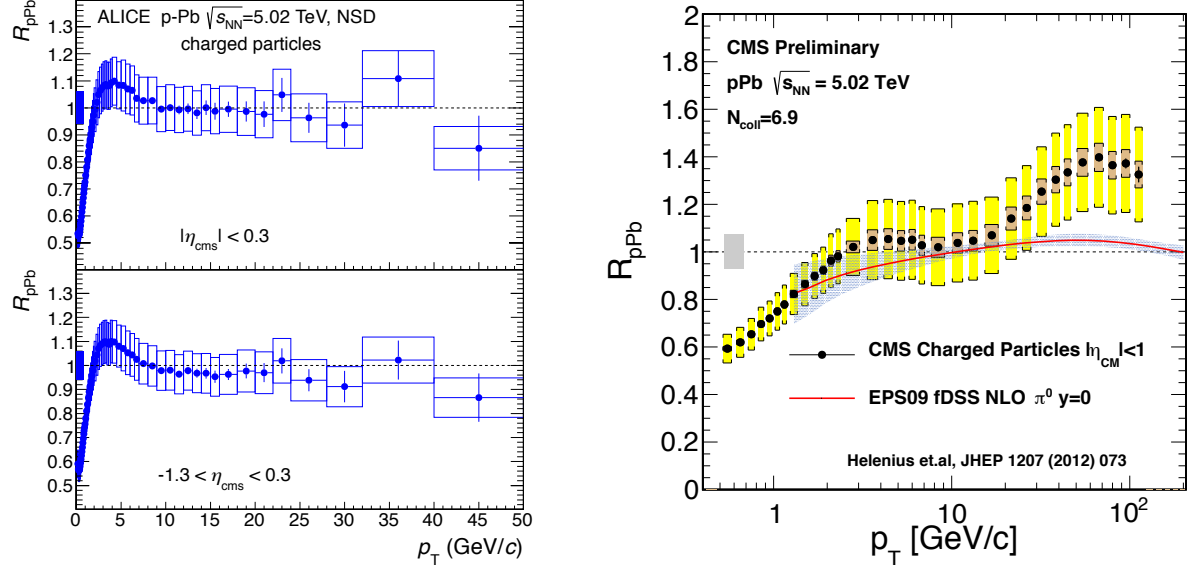

Figure 10. a) (left) ALICE R_{pPb} vs p_T [37] b)(right) CMS preliminary R_{pPb} [38].

GeV/c, while the CMS results agree for $3 \leq p_T \leq 20$ GeV/c, with $R_{\mathrm{pPb}} = 1$, but then show a sharp increase to $R_{\mathrm{pPb}} \approx 1.4$ for $40 \leq p_T \leq 100$ GeV/c, a jump never before seen in such measurements. For comparison the ATLAS jet measurement at $x_T \geq 0.045$ ($p_T \geq 113$ GeV/c) (Fig. 9b) is constant at $R_{\mathrm{pPb}} \approx 1.2 \pm 0.1$. Since there is no $p + p$ comparison measurement for single inclusive particles at $\sqrt{s}$ =5.02 TeV, experience suggests that this is the problem, which must be resolved by a high priority $\sqrt{s}$ =5.02 TeV $p + p$ comparison run when the LHC starts up again.

There were similar "exciting results" at CERN in 1982 which had unexpected consequences.

6.1. Experience is the best teacher. Right?

In 1984, a program of Heavy Ions in the CERN-SPS was approved by the DG, Herwig Schopper, partly due to some "exciting results" from $\alpha - \alpha$ collisions in the CERN-ISR (Fig 11a) [39]. The large value of the $\alpha\alpha/pp$ cross sections in Fig. 11a was WRONG because of an incorrect
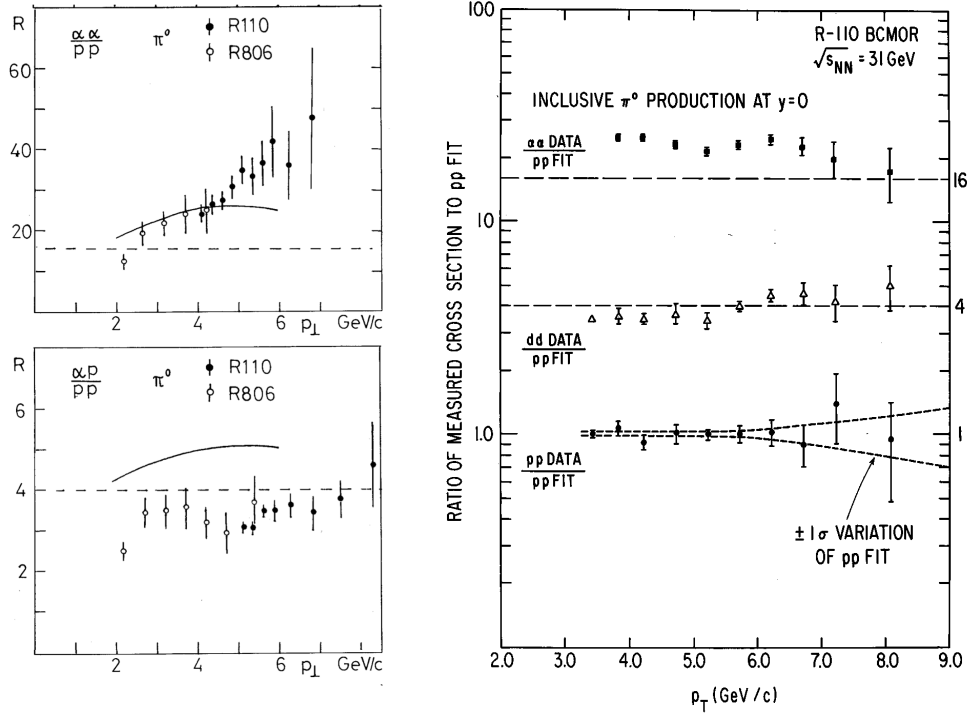

Figure 11. a) (left) Ratio of cross sections in $\alpha + p$ and $\alpha + \alpha$ interactions to the cross sections in $p + p$ interactions as a function of p_T: $R[(\alpha p \to \pi^0 + X)/(pp \to \pi^0 + X)]$ at $\sqrt{s_{NN}} = 44$ GeV and $R[(\alpha\alpha \to \pi^0 + X)/(pp \to \pi^0 + X)]$ at $\sqrt{s_{NN}} = 31$ GeV [40], compiled by Faessler [39]. b) (right) BCMOR measurements [41] of the inclusive π^0 cross sections in $\alpha - \alpha$, $d + d$ and $p + p$ collisions at $\sqrt{s_{NN}} = 31$ GeV divided by a fit to the $p + p$ data.

extrapolation of $p+p$ measurements from $\sqrt{s} = 62.4$ to 31 GeV. I complained about this but I was too busy making magnets at ISABELLE at that time—a lucky break in retrospect. Also, because ISABELLE was cancelled in 1983 and the chair of my department, Arthur Schwartzschild, was a nuclear physicist who had heard of this "exciting result" by the grapevine and wanted to get collider experience for the RHIC proposal, he offered me a small group of nuclear physicists to participate in the 1983 CERN-ISR $p + p$, $d + d$ and $\alpha + \alpha$ run at $\sqrt{s_{NN}} = 31$ GeV (the BCMOR collaboration where B stands for Brookhaven). The correct results are shown in Fig. 11b [41].

This shows that sometimes WRONG RESULTS can have a bigger impact than correct results because they are EXCITING; but this does not excuse making mistakes.

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