A Brief History of Jet Quenching Theory

40 years and counting

Berndt Mueller (Duke Univ.)

Xin-Nian Wang Symposium

August 18, 2022

LBNL

The unpublished origins

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

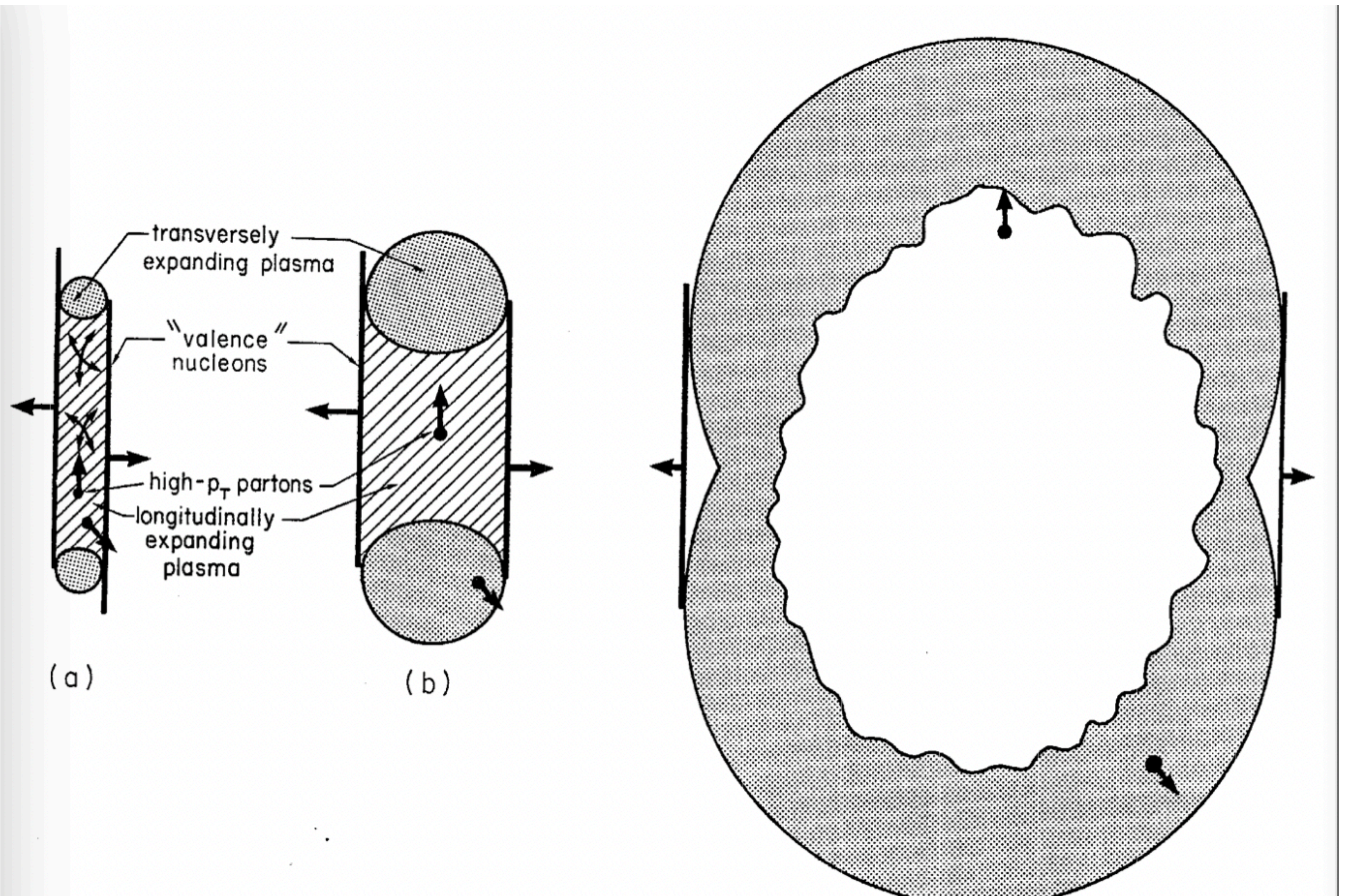


Fig. 1

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Jet Acoplanarity

PHYSICAL REVIEW D VOLUME 33, NUMBER 3 1 FEBRUARY 1986

Jets as a probe of quark-gluon plasmas

David A. Appel
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794

(Received 29 August 1985)

We investigate the propagation of jets through a quark-gluon plasma. The transverse-momentum imbalance of a jet pair is shown to be sensitive to multiple scattering off the constituents of the plasma for expected values of the plasma temperature and size. This raises the possibility that such transverse-momentum imbalance could be used as a probe of a quark-gluon plasma produced by partonic interactions in ultrarelativistic nucleus-nucleus collisions.

Follow-up article by Blaizot & McLerran, Phys. Rev. D 34 (1986) 2739

It was not all theory!

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Concept for an Experiment on Particle and Jet Production at Midrapidity

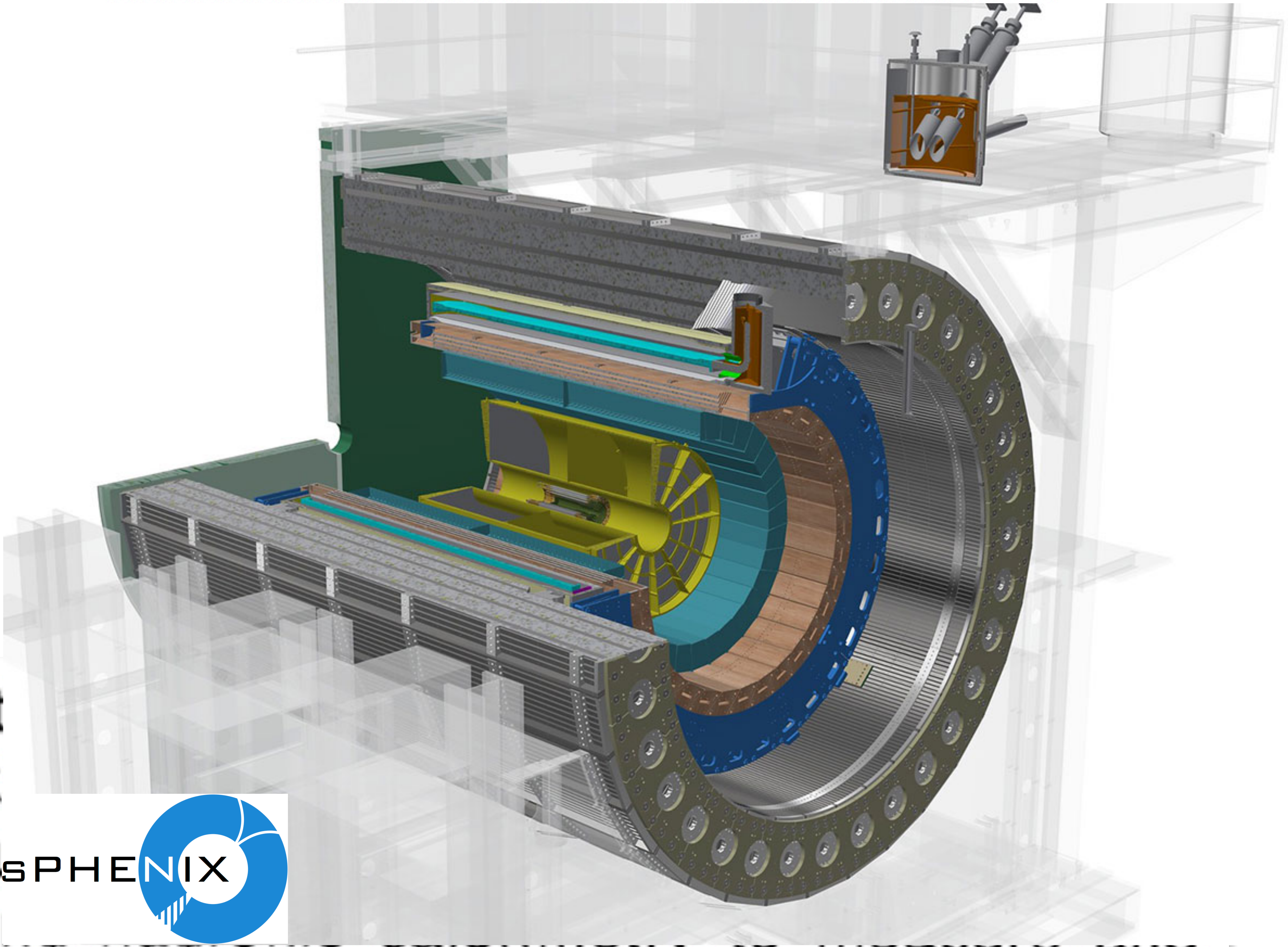
J.W. Harris,[7] M. Bloomer,[7] P. Brady,[1] J. Carroll,[2] S.I. Chase,[7] W. Christie,[7] J. Cramer,[12] E. Friedlander,[7] D. Greiner,[7] C. Gruhn,[7] M. Gyulassy,[7] T. Hallman,[4] E. Hjort,[10] G. Igo,[2] P. Jacobs,[7] K. Kadija,[13] D. Keane,[5] L. Madansky,[4] C. Naudet,[7] D. Nygren,[7] G. Odyniec,[7] D. Olson,[7] G. Paic,[13] A. Poskanzer,[7] G. Rai,[7] H.G. Ritter,[7] R. Scharenberg,[10] L.S. Schroeder,[7] P. Seidl,[7] P. Seyboth,[8] D. Shy,[7] R. Stock,[3] T.J. M. Symons,[7] L. Teitelbaum,[7] M.L. Tincknell,[9] H. van Hecke,[6] X.N. Wang,[7] R. Welsh,[4] W. Wenzel,[7] H. Wieman,[7] and K.L. Wolf[11]

Presented at the Workshop on Experiments and Detectors for RHIC, Upton, NY, July 2–7, 1988, and

Abstract

detection system consists of a vertex det
inside a solenoidal magnet for track
identification; a time-of-flight system surrou
higher momenta; and electromagnetic a
trigger on jets and the transverse energy of events.

RHIC Experiment on Particle and Jet Production



Jet quenching revived

Volume 243, number 4 PHYSICS LETTERS B 5 July 1990

Jet quenching in dense matter

Miklos Gyulassy and Michael Plümer [1]
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

Received 2 March 1990

The quenching of hard jets in ultrarelativistic nuclear collisions is estimated emphasizing its sensitivity to possible changes in the energy loss mechanism in a quark–gluon plasma.

Mentions radiative energy loss but does not estimate its size

Nuclear Physics B351 (1991) 491–506
North-Holland

QUARK DAMPING AND ENERGY LOSS IN THE HIGH TEMPERATURE QCD*

Markus H. THOMA and Miklos GYULASSY
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

Received 23 July 1990

Collective version of collisional energy loss

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{v}{v} q^a \operatorname{Re} E^a_{\mathrm{ind}}(x = vt, t) .$$

The energy loss per unit length of high energy quarks in a quark–gluon plasma is calculated via PQCD. Unlike the damping rate, $\boxed{\text{the energy loss is infrared finite and surprisingly small.}}$

Energy loss is radiative

PHYSICAL REVIEW D VOLUME 44, NUMBER 11 1 DECEMBER 1991

HIJING: A Monte Carlo model for multiple jet production in *pp*, *pA*, and *AA* collisions

Xin-Nian Wang* and Miklos Gyulassy
Nuclear Science Division, Mailstop 70A-3307, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 29 July 1991)

Combining perturbative-QCD inspired models for multiple jet production with low p_T multistring phenomenology, we develop a Monte Carlo event generator HIJING to study jet and multiparticle production in high energy pp, pA, and AA collisions. The model includes multiple minijet production, nuclear shadowing of parton distribution functions, and a schematic mechanism of jet interactions in dense matter. Glauber geometry for multiple collisions is used to calculate pA and AA collisions. The phenomenological parameters are adjusted to reproduce essential features of pp multiparticle production data for a wide energy range ($\sqrt{s}=5$–2000 GeV). Illustrative tests of the model on $p+A$ and light-ion $B+A$ data at $\sqrt{s}=20$ GeV/nucleon and predictions for Au+Au at energies of the BNL Relativistic Heavy Ion Collider ($\sqrt{s}=200$ GeV/nucleon) are given.

The energy loss of a high energy quark or gluon in hot QCD matter has been estimated in Refs. [51–53]. It appears that radiative energy loss due to induced gluon bremsstrahlung in soft final state scatterings dominates the energy loss mechanism. The radiative energy loss per unit length, dE/dx, in the limit of small mean free path $\lambda_s \ll E/\mu^2$ has been estimated to be [53]

$$dE/dx \approx \frac{3\alpha_s}{\pi}\mu^2 \mathcal{L}(E/\lambda_s\mu^2, s/4\mu^2)\,, \tag{41}$$

where $\mathcal{L}(x,y)=\ln x(\ln x-1+1/x)+\ln y(1-x/y)$, E is

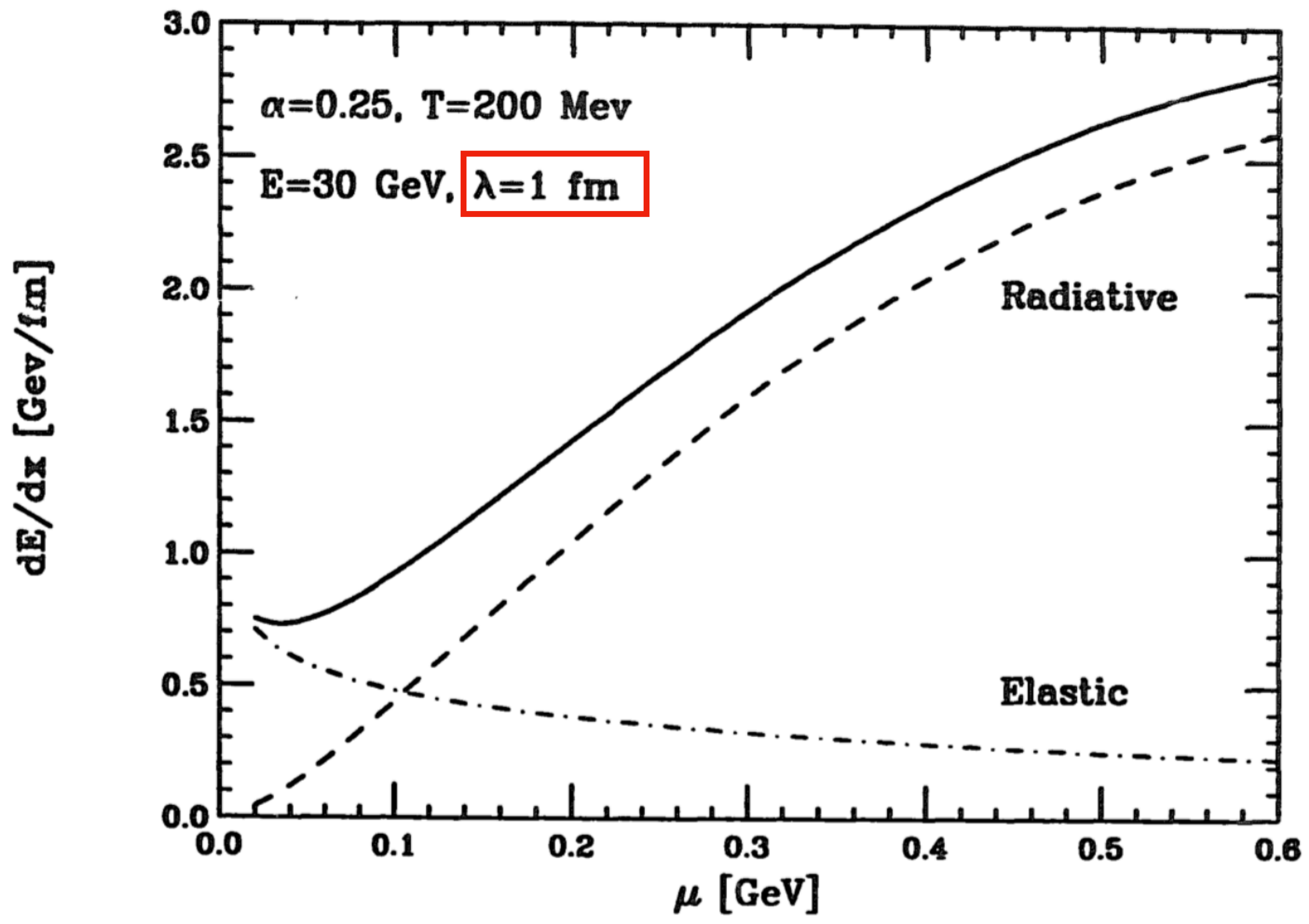
A mystery preprint: LBL-31003

M. Gyulassy and X. N. Wang, Phys. Rev. D44, 3501 (1991). - HIJING: A Monte-Carlo-Model ….

the energy loss mechanism. The radiative energy loss per unit length, dE/dx, in the limit of small mean free path $\lambda_s \ll E/\mu^2$ has been estimated to be [53]

[53] M. Gyulassy, M. Thoma, and X. N. Wang, LBL Report No. LBL-31003, 1991 (unpublished).

Somewhat misleading; You cannot vary μ and keep λ fixed (λ~μ²!)



M. Gyulassy[1], M. Plümer[2], M. Thoma[3], and X.N. Wang[1]

Nuclear Physics A538 (1992) 37c-50c

transitions in nuclear collisions. However, we recently found that at least deep in the QGP phase, the induced radiative energy loss could be quite large[21]. The spectrum of

[21] M. Gyulassy, M. Thoma, X.N. Wang, LBL-31003 (1991) preprint.

Not in SLAC preprint library, not in LBL-NSD, not in the authors' private files. Where is it?

The seminal phenomenological paper

VOLUME 68, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1992

Gluon Shadowing and Jet Quenching in $A+A$ Collisions at $\sqrt{s}=200A$ GeV

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Miklos Gyulassy

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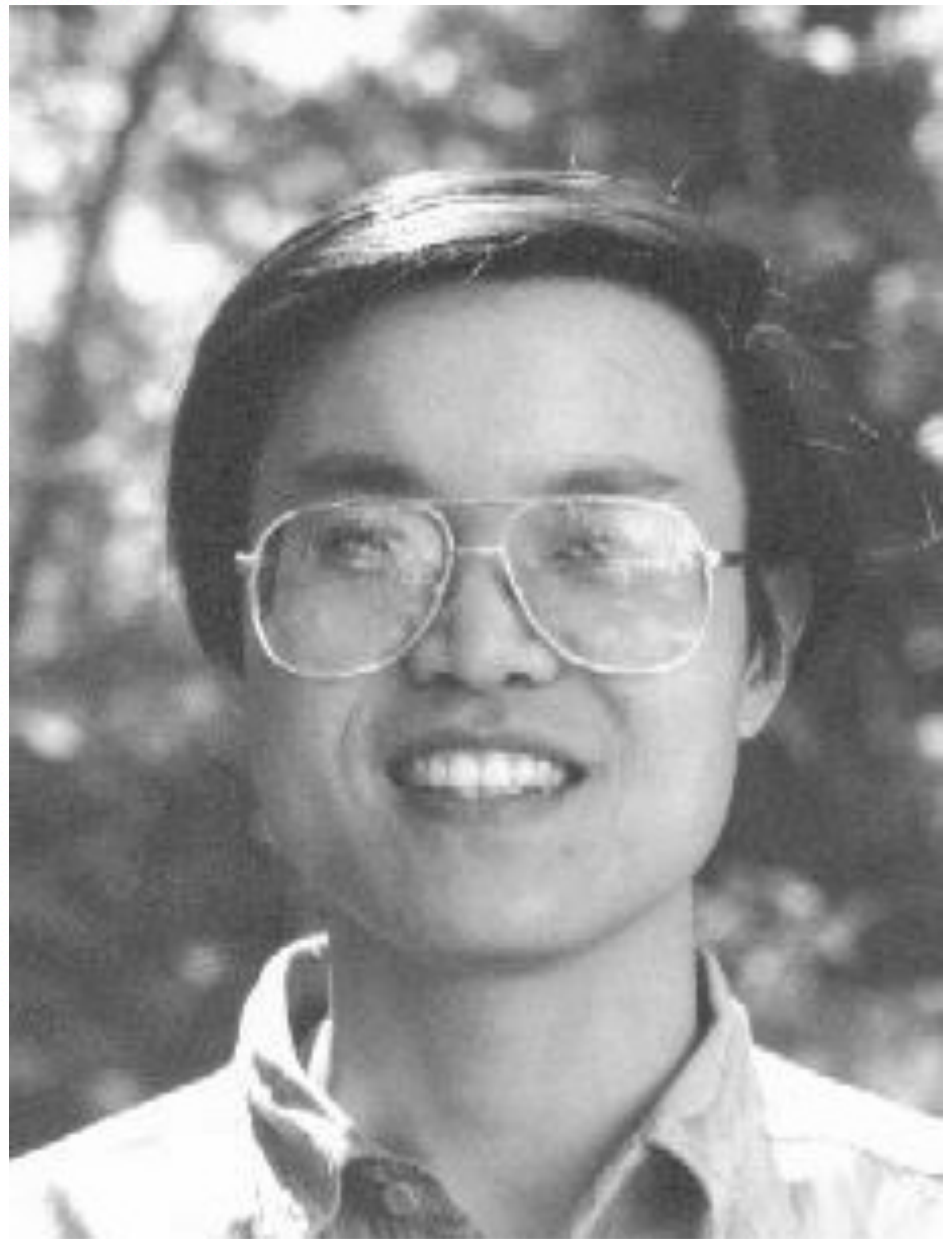
(Received 20 December 1991)

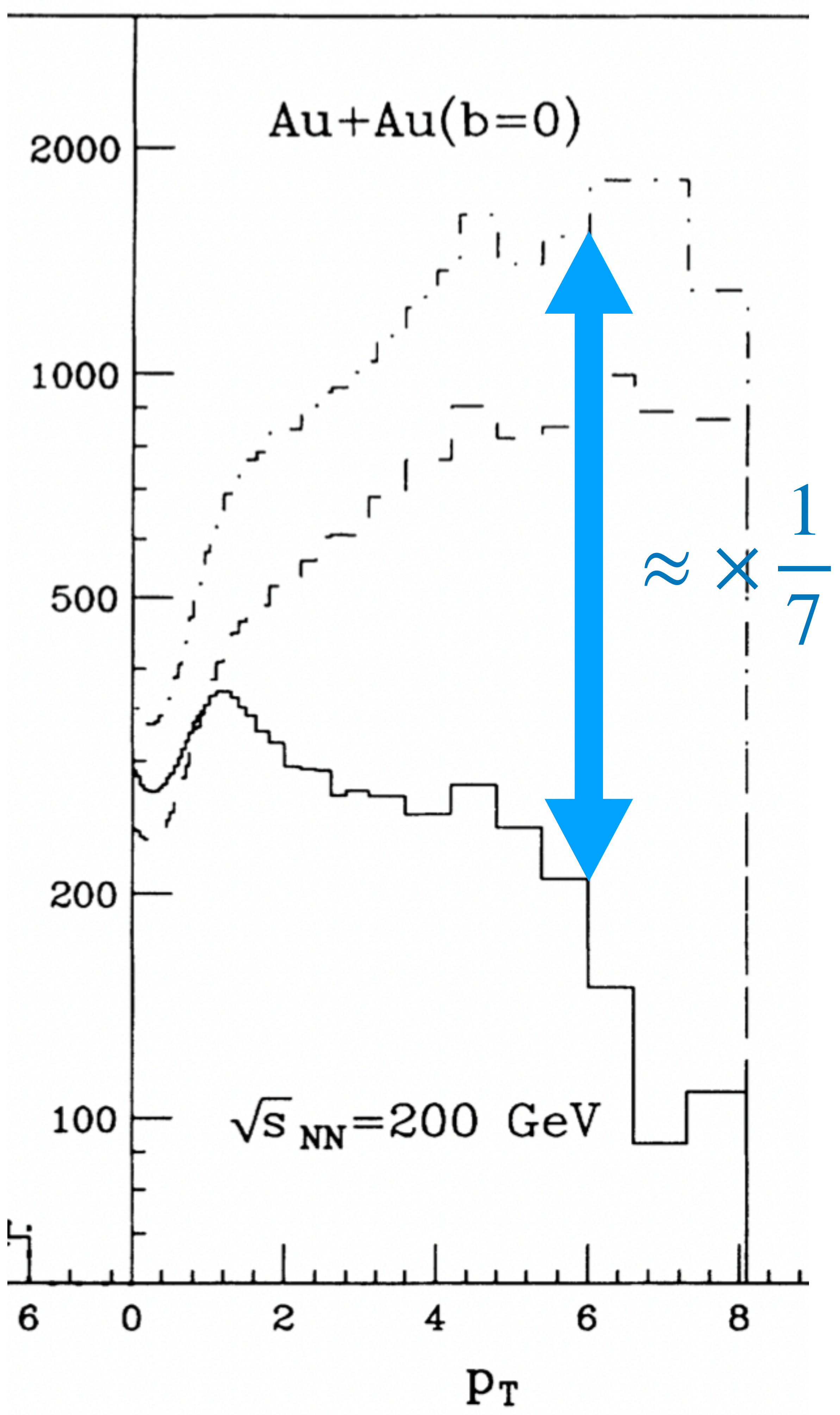
The sensitivity of moderate $p_T \lesssim 8$ GeV/c singles inclusive spectra in nuclear collisions to gluon shadowing and jet quenching is estimated using the HIJING Monte Carlo model. We show how the systematic study of the nuclear dependence of those spectra in $p+A$ can be used to determine the magnitude of gluon shadowing and how the enhanced suppression in $A+A$ would provide information on the energy loss mechanisms in dense partonic matter.

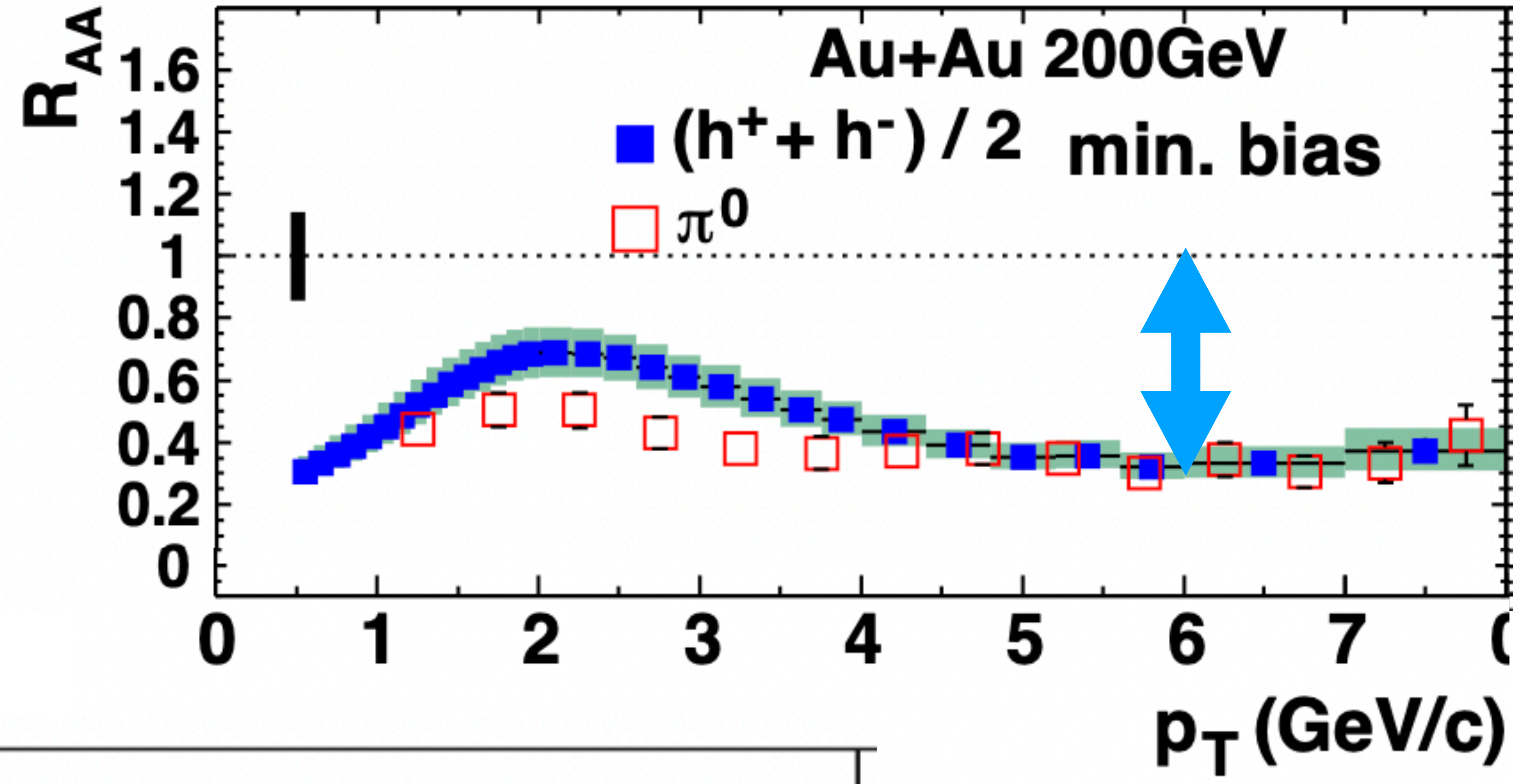


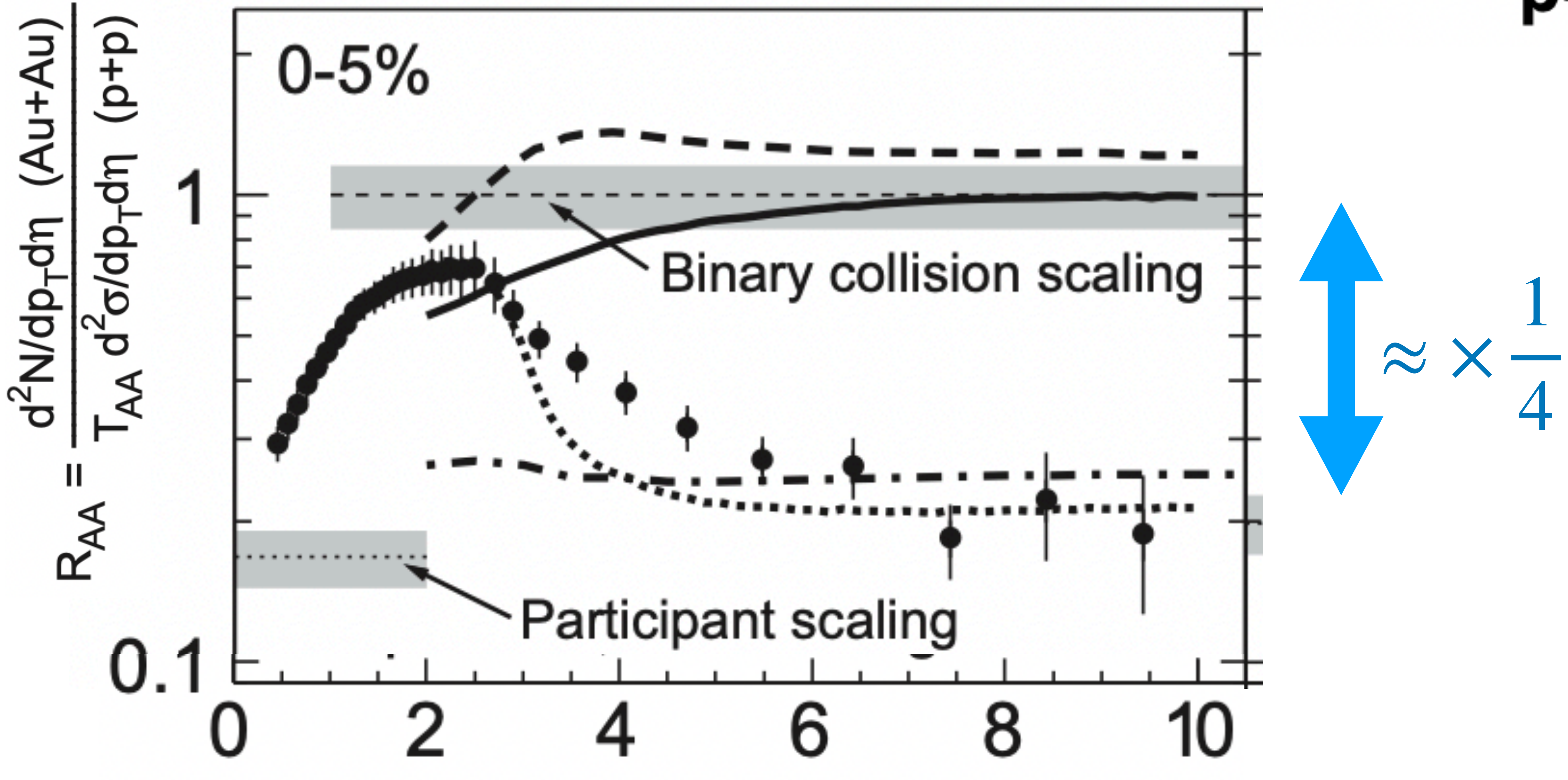
dense matter. PQCD estimates [14] indicate that induced gluon bremsstrahlung may dominate the energy loss mechanism and that $dE/dl \propto \alpha_s \mu_D^2 \ln^2(E/\mu_D) \sim 1-3$ GeV/fm depends sensitively on the infrared (Debye) screening scale μ_D of the medium. Jet quenching therefore provides information on that interesting scale, which may vary significantly in the vicinity of the quark-gluon plasma transition.

HIJING (1991) & RHIC data (2003)

$$R^{AB}(p_T) = \frac{d^2N_{AB}/dp_T^2 d\eta}{d^2N_{pp}/dp_T^2 d\eta}$$







Towards rigorous theory

NUCLEAR PHYSICS B

ELSEVIER Nuclear Physics B 420 (1994) 583–614

Multiple collisions and induced gluon bremsstrahlung in QCD ⋆

Miklos Gyulassy
Physics Department Columbia University, New York, NY 10027, USA

Xin-nian Wang
Nuclear Science Division Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

Received 2 June 1993; revised 27 December 1993; accepted 21 January 1994

Abstract

Induced soft gluon bremsstrahlung associated with multiple collisions is calculated via perturbative QCD. We derive the non-abelian analog of the Landau–Pomeranchuk effect that suppresses induced soft radiation with formation times exceeding the mean free path. The dependence of the suppression effect on the SU(N) representation of the jet parton as well as the kinematic variables is expressed through a radiation formation factor. The soft radiation with $k_\perp < \mu$, where μ is the infrared screening scale in the medium, is shown to lead to an approximately constant radiative energy loss per unit length.

Introduces core principles:

- Multiple scattering with screening length μ^{-1}
- Eikonal limit
- LPM effect

$$dE/dx \propto C_R^2 \mu^2$$

Misses:

- Scattering of the radiated gluon

$$dE/dx \propto N_c C_R \mu^2 (L/\lambda)$$

The complete theory

N·H ELSEVIER

Nuclear Physics B 483 (1997) 291–320
Nuclear Physics B 484 (1997) 265–282

NUCLEAR PHYSICS B

Radiative energy loss of high energy quarks and gluons in a finite-volume quark–gluon plasma

R. Baier[a], Yu.L. Dokshitzer[b,1], A.H. Mueller[c,d,2], S. Peigné[e], D. Schiff[c]
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Received 23 July 1996; accepted 30 September 1996

Radiative energy loss and $p_\perp$-broadening of high energy partons in nuclei

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Received 12 August 1996; revised 10 October 1996; accepted 14 October 1996

Fully quantum treatment of the Landau-Pomeranchik-Migdal effect in QED and QCD

B. G. Zakharov

Journal of Experimental and Theoretical Physics Letters **63**, 952–957 (1996)

Abstract

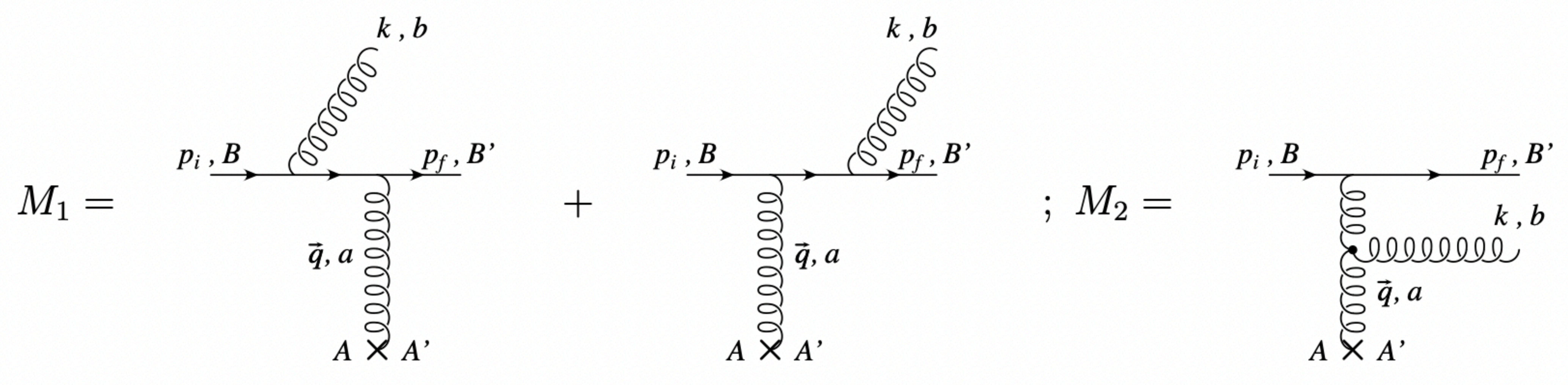
A rigorous quantum treatment of the Landau-Pomeranchuk-Migdal effect in QED and QCD is given for the first time. The rate of photon (gluon) radiation by an electron (quark) in a medium is expressed in terms of the Green's function of a two-dimensional Schrödinger equation with an imaginary potential. In QED this potential is proportional to the dipole cross section for scattering of an e^+e^- pair off an atom, while in QCD it is proportional to the cross section of interaction of the color singlet quark-antiquark-gluon system with a color center.

Landau-Pomeranchuk-Migdal effect for finite-size targets

B. G. Zakharov

Journal of Experimental and Theoretical Physics Letters **64**, 781–787 (1996)

BDMPS-Z theory



Eikonal transverse potential: $V(Q^2) = \dfrac{1}{\pi\sigma} \dfrac{d\sigma}{dQ^2} \longrightarrow \hat{q}_U = \int d^2\vec{Q}\, Q^2 V(Q^2)$

Energy loss rate: $-\dfrac{dE}{dz} = \dfrac{\alpha_s C_R}{8} \dfrac{\mu^2}{\lambda_g} \tilde{v}(\tilde{\lambda}/L)\ L$

Hard Probes collaboration

International Journal of Modern Physics A, Vol. 10, Nos. 20 & 21 (1995) 2881–2883
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The second reason – and in fact its original trigger – is the search for the quark-gluon plasma in high energy nuclear collisions. This new state of matter, predicted by statistical QCD, consists of deconfined quarks and gluons of high density, and to check if the early phases of nuclear collisions have indeed produced such a plasma, sufficiently hard probes are needed to resolve the short distance nature of the medium. Hard processes in hadronic collisions probe the partonic nature of hadrons and are therefore ideally suited for this endeavor. In hadronic matter,

In order to use them for this purpose, we should first understand the basic process, in the absence of any medium, and then check what modifications each basic process experiences in confined hadronic matter. After these two "normalisation" steps, we would be prepared to look for parton deconfinement.

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- open charm,
- quarkonium states,
- hard jets.

For each of these, we shall discuss the present theoretical understanding, compare the resulting predictions to available data, and then show what behaviour it leads to at RHIC and LHC energies. All of these processes have the structure mentioned above: they contain a hard partonic interaction, calculable perturbatively, but also the non-perturbative parton distribution within a hadron. These parton distributions, however, can be studied theoretically in terms of counting rule arguments, and they can be checked independently by measurements of the parton structure functions in deep inelastic lepton-hadron scattering.

Tagged jets

VOLUME 77, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 1996

Jet Quenching in the Direction Opposite to a Tagged Photon in High-Energy Heavy-Ion Collisions

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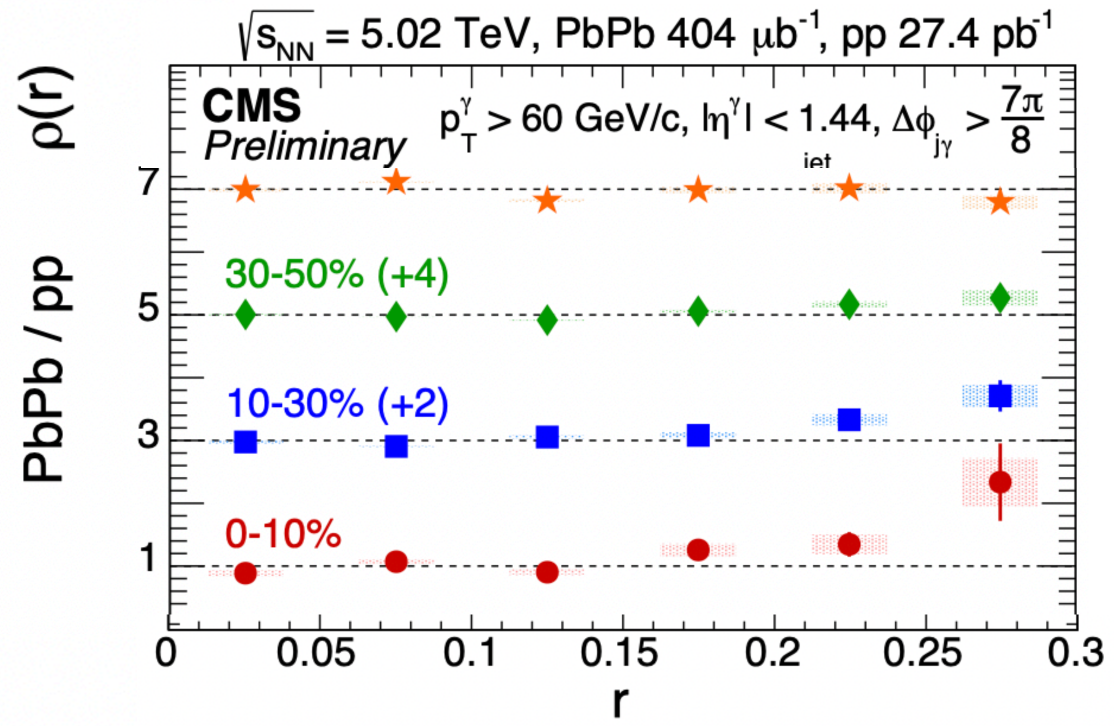
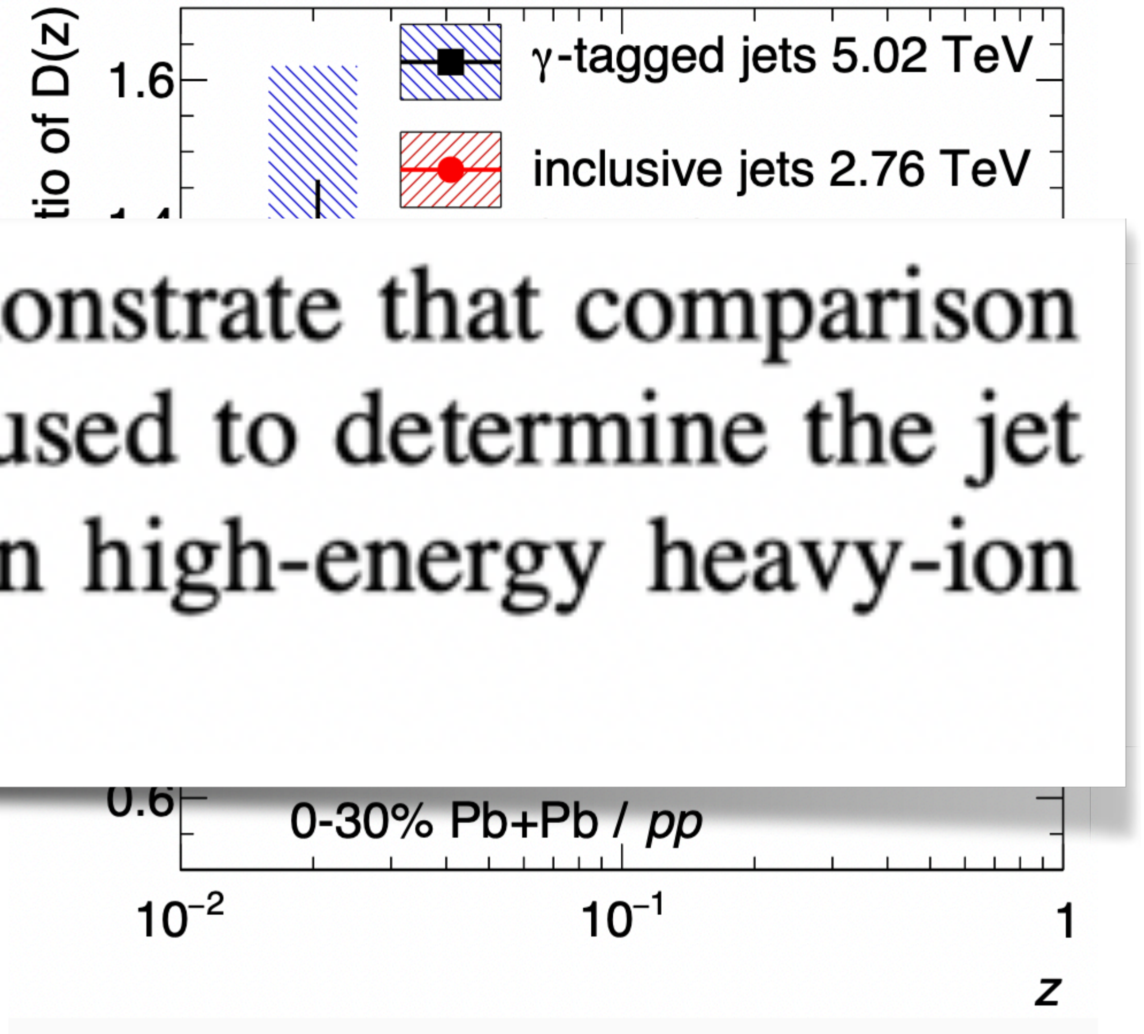
Zheng Huang and Ina Sarcevic

Department of Physics, University of Arizona, Tucson, Arizona 85721

(Received 5 March 1996; revised manuscript received 3 May 1996)

We point out that events associated with large E_T direct photons in high-energy heavy-ion collisions can be used to study jet energy loss in dense matter. In such events, the p_T spectrum of charged hadrons





We demonstrate that comparison between the extracted fragmentation function in AA and pp collisions can be used to determine the jet energy loss and the interaction mean free path in the dense matter produced in high-energy heavy-ion collisions.

Opacity expansion

VOLUME 85, NUMBER 26 PHYSICAL REVIEW LETTERS 25 DECEMBER 2000

Non-Abelian Energy Loss at Finite Opacity

M. Gyulassy,[1] P. Levai,[1,2] and I. Vitev[1]
[1]Department of Physics, Columbia University, 538 West 120th Street, New York, New York 10027
[2]KFKI Research Institute for Particle and Nuclear Physics, P.O. Box 49, Budapest, 1525, Hungary
(Received 12 May 2000)

A systematic expansion in opacity, L/λ, is used to clarify the nonlinear behavior of induced gluon radiation in quark-gluon plasmas. The inclusive differential gluon distribution is calculated up to second order in opacity and compared to the zeroth order (factorization) limit. The opacity expansion makes it possible to take finite kinematic constraints into account that suppress jet quenching in nuclear collisions below RHIC ($\sqrt{s} = 200$ AGeV) energies.

Nuclear Physics B 594 (2001) 371–419

Reaction operator approach to non-abelian energy loss

M. Gyulassy [a], P. Levai [a,b,*], I. Vitev [a]
[a] Department of Physics, Columbia University, 538 W 120-th Street, New York, NY 10027,USA
[b] KFKI Research Institute for Particle and Nuclear Physics, P.O. Box 49, Budapest, 1525, Hungary

Higher-twist formalism

ELSEVIER

NUCLEAR PHYSICS A

Nuclear Physics A 696 (2001) 788–832

Multiple parton scattering in nuclei: parton energy loss

Xin-Nian Wang [a,*], Xiaofeng Guo [b]

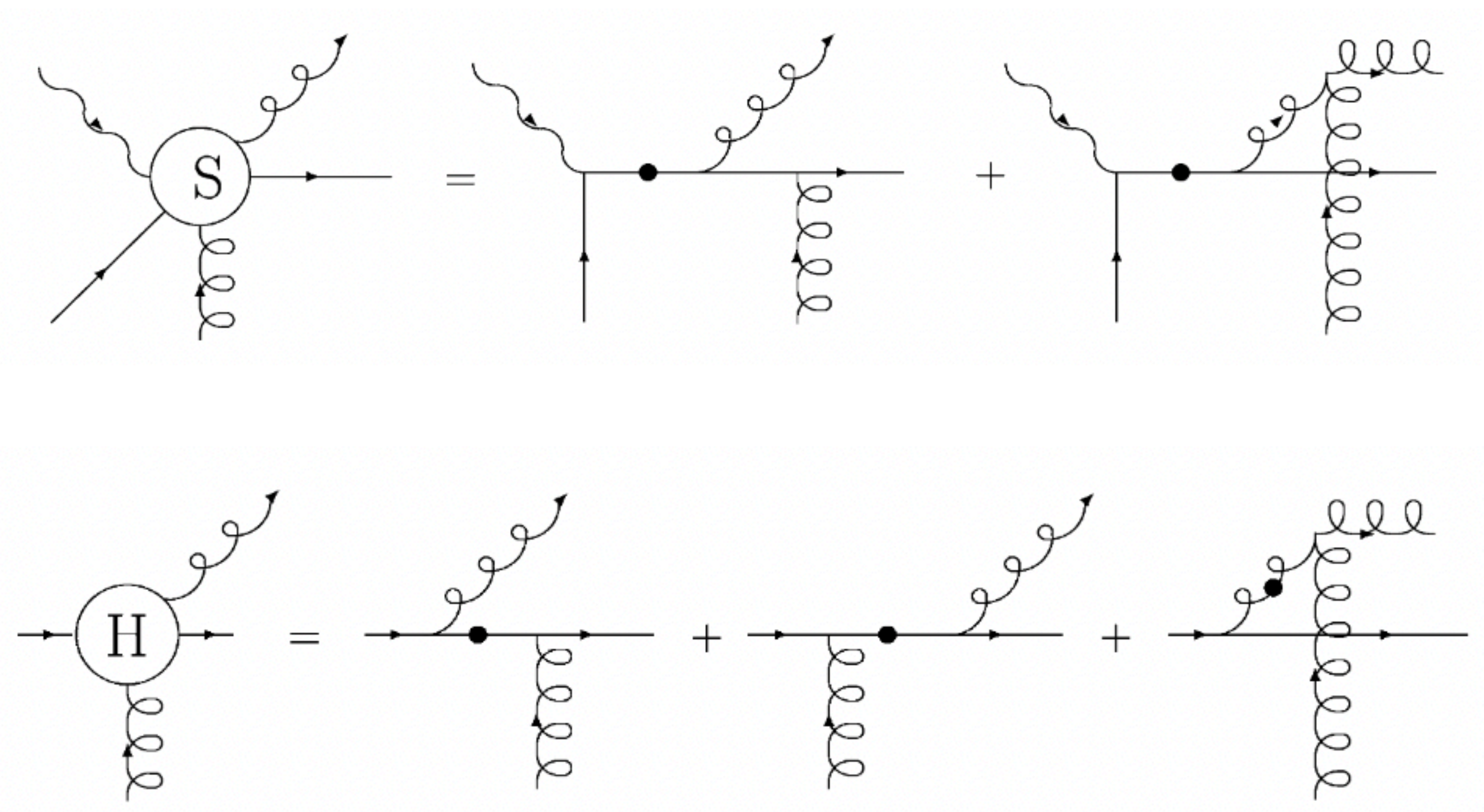
[a] *Nuclear Science Division, Mailstop 70-319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

[b] *Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky, KY 40506, USA*

Received 12 March 2001; revised 7 May 2001; accepted 18 May 2001

Abstract

Multiple parton scattering and induced parton energy loss are studied in deeply inelastic scattering (DIS) off nuclei. The effect of multiple scattering of a highly off-shell quark and the induced parton energy loss is expressed in terms of the modification to the quark fragmentation functions. We derive such modified quark fragmentation functions and their QCD evolution equations in DIS using the generalized factorization of higher twist parton distributions. We consider double-hard and hard-soft parton scattering as well as their interferences in the same framework. The final result, which depends on both the diagonal and off-diagonal twist-four parton distributions in nuclei, demonstrates clearly the Landau–Pomeranchuk–Migdal interference features and predicts a unique nuclear modification of the quark fragmentation functions. 2001 Elsevier Science B.V. All rights reserved.



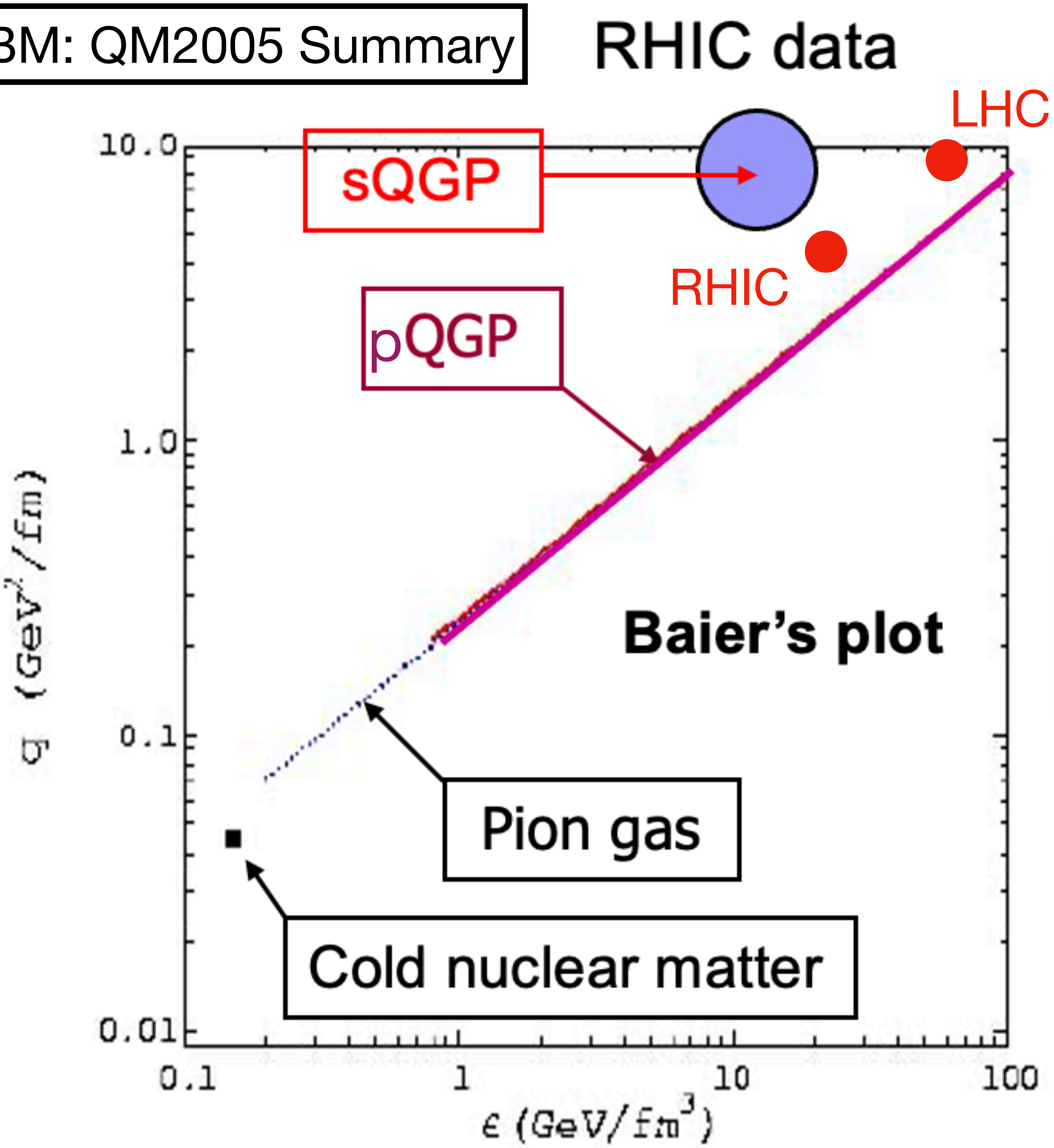
Modified DGLAP equations:

$$\frac{\partial \widetilde{D}_{q\to h}(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi}\int_{z_h}^{1}\frac{dz}{z}\Big[\tilde{\gamma}_{q\to qg}(z,x,x_L,\mu^2)\widetilde{D}_{q\to h}(z_h/z,\mu^2) + \tilde{\gamma}_{q\to gq}(z,x,x_L,\mu^2)D_{g\to h}(z_h/z,\mu^2)\Big].$$

Core approach in JETSCAPE

The 2005 crisis

BM: QM2005 Summary



To the Rescue:

TEC-HQM

Theory-Expt. Collaboration

On Hot Quark Matter

PHYSICAL REVIEW C **86**, 064904 (2012)

Comparison of jet quenching formalisms for a quark-gluon plasma "brick"

Nestor Armesto,[1] Brian Cole,[2] Charles Gale,[3] William A. Horowitz,[4,5] Peter Jacobs,[6] Sangyong Jeon,[3] Marco van Leeuwen,[7] Abhijit Majumder,[4,8] Berndt Müller,[9] Guang-You Qin,[9] Carlos A. Salgado,[1] Björn Schenke,[3,10] Marta Verweij,[7] Xin-Nian Wang,[11,6] and Urs Achim Wiedemann[12]

We review the currently available formalisms for radiative energy loss of a high-momentum parton in a dense strongly interacting medium. The underlying theoretical framework of the four commonly used formalisms is discussed and the differences and commonalities between the formalisms are highlighted. A quantitative comparison of the single-gluon emission spectra as well as the energy-loss distributions is given for a model system consisting of a uniform medium with a fixed length of $L = 2$ fm and $L = 5$ fm (the "Brick"). Sizable quantitative differences are found. The largest differences can be attributed to specific approximations that are made in the calculation of the radiation spectrum.

JET Collaboration

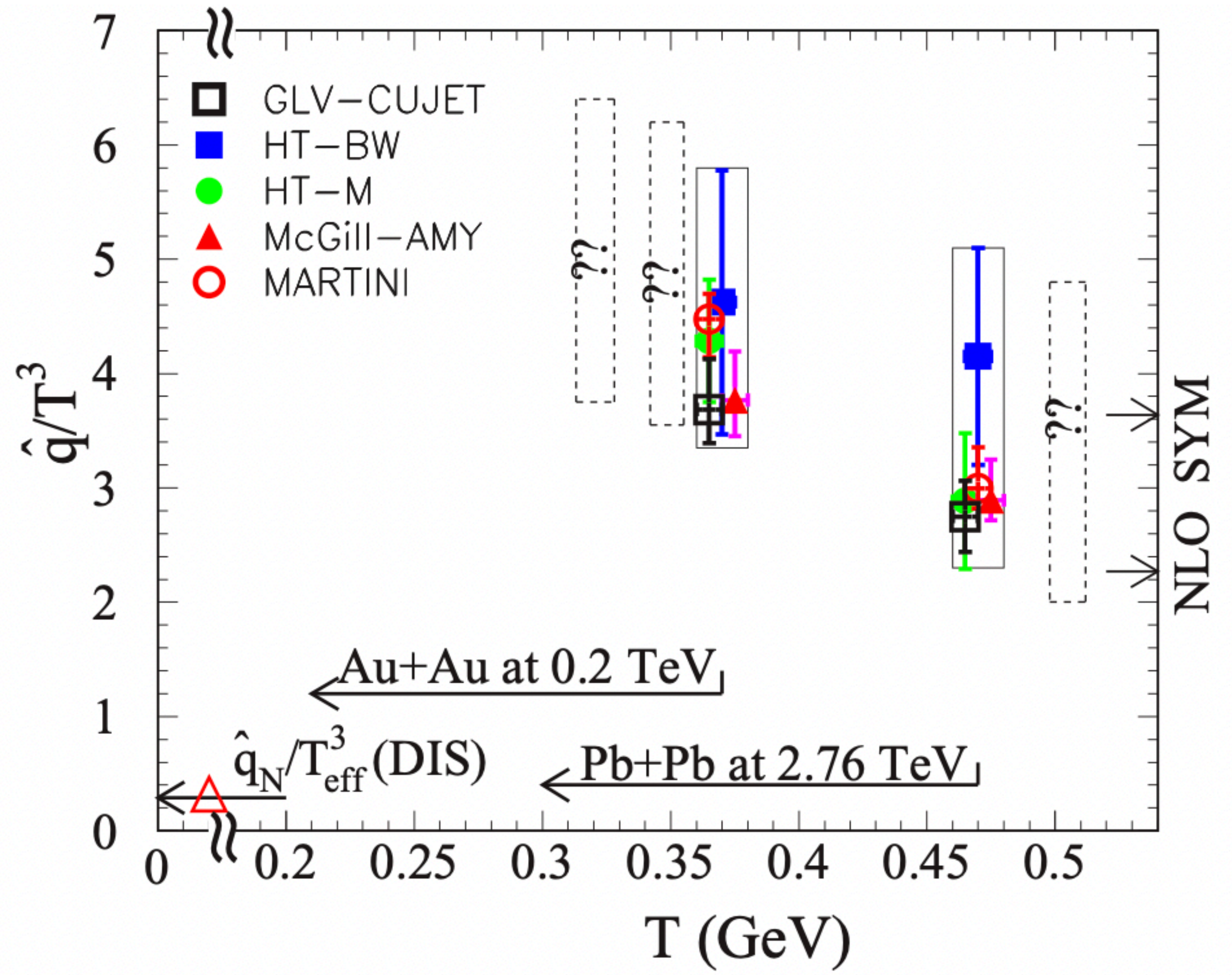
Proposal for a Topical Collaboration on

Quantitative Jet and Electromagnetic Tomography (JET) of Extreme Phases of Matter in Heavy-ion Collisions

for the period of
May 1, 2010 – April 30, 2015

Co-Spokespersons: Berndt Mueller (Duke University) and Xin-Nian Wang (LBNL)

Principal Investigator:
Xin-Nian Wang
Nuclear Science Division, MS70R0319,
Lawrence Berkeley National Laboratory, Berkeley, CA 94720



PHYSICAL REVIEW C **90**, 014909 (2014)

Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions

Karen M. Burke,[1] Alessandro Buzzatti,[2] Ningbo Chang,[3] Charles Gale,[4] Miklos Gyulassy,[5] Ulrich Heinz,[6] Sangyong Jeon,[4] Abhijit Majumder,[1] Berndt Müller,[7] Guang-You Qin,[1,3] Björn Schenke,[7] Chun Shen,[6] Xin-Nian Wang,[2,3,*] Jiechen Xu,[5] Clint Young,[8] and Hanzhong Zhang[3]
(JET Collaboration)

Today’s frontier: Jet substructure

- Fragmentation functions
- Jet shape
- Jet invariant mass
- Lund plane
- Groomed jets
- Track functions
- Energy flow correlators
- etc. etc. etc.

A rich playground for theorists and experimentalists alike

Theoretical description requires Monte-Carlo simulation: JETSCAPE, JEWEL, ….

and

Realistic modeling of the underlying event

Summary

Jet quenching is a vibrant field of theoretical and experimental investigation.

It has moved from the study of parton energy loss to the study of modification of jet structure by the surrounding medium. It promises to be at the center of experimental programs at RHIC, LHC and in the future, EIC.

1962

2022

As a true “Tiger” Xin-Nian has pounced and made his deep mark on the field of jet quenching.

The future is bright

Happy Birthday, Xin-Nian!